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SCIENTIFIC PUBLICATIONS' BIBLIOMETRIC ANALYSIS OF APPLICATION-LEVEL TCP/IP MODELS' COMMUNICATION PROTOCOLS FOR THE INTERNET OF THINGS

A bibliometric analysis of publications on application-layer communication protocols in the context of the Internet of Things technologies have been conducted. The study highlights significant disparities in scientific attention given to various protocols, emphasizing the dominance of MQTT and CoAP in the scientific literature. Data from the Scopus bibliometric database were used to evaluate the level of research activity and the scientific community's interest in MQTT, MQTT-SN, CoAP, STOMP, XMPP, WAMP, AMQP, DDS, OPC UA, and LwM2M protocols. The findings reveal which protocols are at the forefront of contemporary research and hold the most significant potential for further development and implementation in IoT systems. Understanding the current state and prospects of communication protocols provides an essential foundation for developers and researchers to select optimal solutions for IoT systems integration.

The relevance of the topic. Despite the immense potential of the Internet of Things to optimize processes and create innovative services, there is a need for more detailed analyses of the relevance and prospects of various application-layer communication protocols in this field. This creates a gap in understanding how to integrate these protocols into IoT systems, their challenges and opportunities, and which strategies may effectively address them. A systematic approach and in-depth analysis of these protocols are critical for developers when selecting optimal solutions for their implementation in IoT systems.

The purpose of the article. To conduct an updated bibliometric analysis of open application-layer communication protocols within the TCP/IP framework, specifically MQTT, MQTT-SN, CoAP, STOMP, XMPP, WAMP, AMQP, DDS, OPC UA, and LwM2M are applied. The analysis aims to evaluate the level of research activity and the degree of scientific community interest in each protocol using data from the Scopus bibliometric database.

The methodology includes data collection and analysis methods from the Scopus database, focusing on publications from the inception of each protocol until 2023. The study filters publications by fields of knowledge and document types to ensure relevance and significance.

Conclusions. The study revealed a considerable dominance of MQTT and CoAP protocols in the domain of the Internet of Things. With its message delivery control levels, client-broker architecture, network quality and speed resilience, detailed documentation, and low resource requirements, MQTT demonstrates considerable advantages over other protocols in most use cases. The CoAP protocol is more

suitable for scenarios with such potential data loss as streaming multimedia. Other protocols exhibit primarily specific applications and demonstrate low interest from the scientific community. These findings coordinate with the study's purpose and provide a foundation for further research and informed protocol selection in IoT system development.

Keywords*: Internet of Things, IoT, bibliometric analysis, communication protocols, MQTT, CoAP, application-level protocols, digitalization.*

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БІБЛІОМЕТРИЧНИЙ АНАЛІЗ НАУКОВИХ ПУБЛІКАЦІЙ ПРОТОКОЛІВ КОМУНІКАЦІЇ МОДЕЛЕЙ TCP/IP ДЛЯ ІНТЕРНЕТУ РЕЧЕЙ ПРИКЛАДНОГО РІВНЯ

Здійснено бібліометричний аналіз публікацій щодо комунікаційних протоколів прикладного рівня в контексті технологій Інтернету речей. Дослідження висвітлює значну нерівність у науковій увазі до різних протоколів, підкреслюючи домінування MQTT та CoAP у науковій літературі. Для оцінки рівня дослідницької активності та зацікавленості наукової спільноти щодо протоколів MQTT, MQTT-SN, CoAP, STOMP, XMPP, WAMP, AMQP, DDS, OPC UA та LwM2M було використано дані наукометричної бази Scopus. Результати дозволяють виявити, які протоколи перебувають у центрі уваги сучасних досліджень та мають найбільший потенціал для подальшого розвитку і впровадження в системах IoT. Розуміння поточного стану та перспектив цих комунікаційних протоколів надає важливу основу для розробників та дослідників у виборі оптимальних рішень для інтеграції в IoT-системи.

Ключові слова*: Інтернет речей, IoT, бібліометричний аналіз, комунікаційні протоколи, MQTT, CoAP, протоколи прикладного рівня, цифровізація.*

Problem statement. The correct choice of application-level communication protocols like TCP/IP is critically important for successfully implementing the Internet of Things (IoT) systems, in contemporary world of technologies developing at an improbable speed. Despite the enormous potential of IoT in optimizing processes and creating innovative services, there is a lack of research that thoroughly analyzes the relevance and prospects of different communication protocols in this field. This creates a gap in understanding how to integrate these protocols into IoT systems, the challenges and opportunities this integration brings, and the strategies that may be effective in addressing them. The absence of in-depth analysis and a systematic approach to studying these protocols also limits developers' ability to choose the best solutions for implementing IoT systems.

State of problem development. In the scientific community, several studies are dedicated to comparing and analyzing communication protocols for IoT systems. In particular, the article by Wytrębowicz, Cabaj, and Krawiec (2021) titled "Messaging Protocols for IoT Systems — Pragmatic Comparison" provides a comparative analysis of different protocols. However, there is a lack of

comprehensive bibliometric analysis that evaluates the level of research on each of these protocols and the degree of interest from the scientific community in them, which limits the ability to gain a deeper understanding of the popularity and potential of these technologies in the field of the Internet of Things. Protocols frequently mentioned in scientific publications usually have broader applications and better support from the developer community, which is an essential factor when choosing a protocol for integration into an IoT system.

Purpose of the study. The purpose of this work is to conduct an updated bibliometric analysis of open application-level TCP/IP communication protocols, specifically MQTT, MQTT-SN, CoAP, STOMP, XMPP, WAMP, AMQP, DDS, OPC UA, and LwM2M. The analysis focuses on evaluating the level of research for each protocol and the degree of interest from the scientific community, using data from the Scopus scientometric database. This will help identify which protocols are at the forefront of current research and have the greatest potential for further development and implementation in Internet of Things systems.

Presentation of the main research material. To obtain statistical data reflecting the level of research activity regarding the use of specific communication protocols in the context of the Internet of Things technologies, an analysis was conducted using the scientometric database Scopus. To ensure the relevance and accuracy of the results, data filtering included publications from the date of the first available publication up to and including 2023. For a more thorough study, works belonging to the fields of computer science, engineering, and social sciences were selected, allowing a focus on the interdisciplinary aspects of the development and implementation of protocols in various application areas.

A single, specially formulated query was used to perform the search, with the name of the protocol under investigation serving as the variable. The query had the following format: “TITLE-ABS-KEY (“protocol_name” AND protocol AND iot) AND PUBYEAR < 2024 AND (LIMIT-TO (SUBJAREA , “ENGI”) OR LIMIT-TO (SUBJAREA , “COMP”) OR LIMIT-TO (SUBJAREA , “SOCI”)) AND (LIMIT-TO (DOCTYPE , “cp”) OR LIMIT-TO (DOCTYPE , “ar”) OR LIMIT-TO (DOCTYPE , “ch”))”. For example, to analyze publications related to the MQTT protocol, the following query was used: “TITLE-ABS-KEY (“MQTT” AND protocol AND iot) AND PUBYEAR < 2024 AND (LIMIT-TO (SUBJAREA , “ENGI”) OR LIMIT-TO (SUBJAREA , “COMP”) OR LIMIT-TO (SUBJAREA , “SOCI”)) AND (LIMIT-TO (DOCTYPE , “cp”) OR LIMIT-TO (DOCTYPE , “ar”) OR LIMIT-TO (DOCTYPE , “ch”))”. Thus, for each of the protocols (MQTT, MQTT-SN, CoAP, STOMP, XMPP, WAMP, AMQP, DDS, OPC UA, and LwM2M), the same search query was applied, with only the protocol name in the keywords being changed.

The formulated query ensured the selection of publications in which the keywords "protocol_name", "protocol", and "IoT" are present in the title, abstract, or keywords of the articles. The restriction on the publication period up to and including 2023 was introduced to obtain statistics for complete years of the analysis period and to identify long-term trends in the development of protocols in the context of computer science, engineering, and the social aspects of their application. The analysis of the annual number of publications allowed not only the assessment of the current state of research but also the tracking of their development dynamics over time.

Additional filtering was performed based on document types, specifically including articles, conference papers, and book chapters. The purpose of this refinement was to focus on the most scientifically significant publications that represent key research and development results in the field of IoT. This approach permitted the exclusion of less significant materials, such as short communications, reviews, or technical documentation, and concentrated on documents that have the greatest impact on the advancement of science and technology.

The results obtained from the Scopus database for the analysis of the total number of publications using the keywords MQTT, MQTT-SN, CoAP, STOMP, XMPP, WAMP, AMQP, DDS, OPC UA, and LwM2M with the specified filtering criteria are presented in Table 1.

Table 1

Total Number of Publications on Selected IoT Communication Protocols Based on Scopus Data up to 2023

Protocol	MQTT	MQTT-SN	CoAP	STOMP	XMPP	WAMP	AMQP	DDS	OPC UA	LwM2M
Number of publications	1831	54	995	4	116	1	136	80	85	62

The analysis of Scopus data up to 2023, starting from the year of the first indexed scientific document for each protocol, allows for several key conclusions about research activity in the field of IoT.

The MQTT protocol is the undisputed leader, with 1,831 publications. Its popularity stems from its simplicity, reliability, and broad application across various domains of the Internet of Things.

In second place is the CoAP protocol, with 995 publications, highlighting its significance in the context of resource efficiency and the capability for non-guaranteed data delivery.

MQTT-SN, an extension of the MQTT protocol designed for resource-constrained devices, has 54 publications. This indicates interest in its application in scenarios where optimizing energy consumption and network traffic is critical.

The AMQP and XMPP protocols also attract researchers' attention, with 136 and 116 publications, respectively. These protocols are significant in specialized fields that require reliable messaging mechanisms and support for complex network topologies.

Other protocols, such as DDS (80 publications), OPC UA (87 publications), and LwM2M (62 publications), expose a moderate level of research activity. This may be attributed to their narrow specialization or limited application compared to the leading protocols.

STOMP and WAMP have a minimal number of publications, indicating limited interest from the scientific community or their specific niche roles in IoT systems.

Overall, the analysis conducted from the time of the first indexed publications for each protocol highlights the leading role of MQTT and CoAP in research concomitant to the implementation of IoT technologies. Other protocols have a lesser impact, prompting a more detailed examination of bibliometric indicators to identify trends and research prospects within the scientific community.

A detailed analysis revealed that the most influential publication for the MQTT, CoAP, AMQP, XMPP, and DDS protocols is the article *"Internet of Things: A Survey on Enabling Technologies, Protocols, and Applications"*, published in *IEEE Communications Magazine* in 2015. This article has been cited 6,163 times in Scopus and holds an FWCI of 163.57.

This article provides a comprehensive overview of IoT, focusing on technologies, protocols, and applications. The authors explored how advancements in RFID, smart sensors, and communication technologies have contributed to the evolution of IoT, emphasizing the potential for devices to interact autonomously without human involvement.

The article includes an in-depth analysis of relevant protocols, helping researchers understand their interactions without requiring a detailed study of the standards. It also examines IoT's connection with modern technologies, such as big data analytics and cloud computing, highlighting the need for deeper integration of IoT services.

The article's high citation number confirms its significance as a foundational work that has greatly contributed to the dissemination of knowledge about IoT protocols and technologies among researchers and developers.

To simplify the analysis, protocols with a small number of publications were grouped into a separate category. Specifically, the protocols AMQP, XMPP, DDS, OPC UA, LwM2M, STOMP, and WAMP were combined into the group "Non-Leading Protocols Combined". Additionally, as part of the study, the MQTT-SN protocol was classified as a variation of the MQTT protocol in accordance with its specification.

As a result of the formulated queries, statistical data were obtained, reflecting the annual publication dynamics. These data are presented in Table 2 and visualized as a trend chart in Figure 1, based on the same table.

Table 2

Annual Number of Publications on IoT Communication Protocols from 2011 to 2023 According to Scopus (Grouped by Impact)

Year	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
MQTT Family	0	2	0	19	44	117	215	279	242	299	294	296	358
CoAP	4	28	27	30	51	83	94	134	127	120	109	104	84
Non-Leading Protocols Combined	2	5	6	3	21	25	45	66	62	64	72	57	56

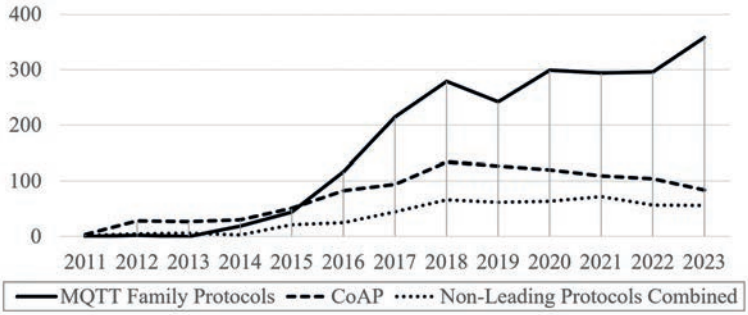

Fig. 1. Trends of Publications on IoT Communication Protocols from 2011 to 2023 According to Scopus (Grouped by Impact)

The analysis of the data in Table 2 highlights the significant dominance of the MQTT protocol in IoT research. Starting in 2012 with just two publications, the number of scientific works dedicated to MQTT has grown rapidly, reaching 358 publications by 2023. This trend indicates a consistent and stable increase in the scientific community's interest in this protocol, affirming its key role and popularity in the development of IoT systems.

The CoAP protocol, ranking second, demonstrates a less pronounced growth trend. Following a peak in 2018 with 134 publications, there has been a gradual decline to 84 publications in 2023. This may indicate waning interest among researchers in CoAP or a shift in focus toward other technologies.

The combined group of non-leading protocols, which includes AMQP, XMPP, DDS, OPC UA, LwM2M, STOMP, and WAMP, shows relatively stable but low levels of research activity. The number of publications for these protocols fluctuates between 56 and 72 per year from 2017 to 2023. This suggests that while

these protocols have their applications in specific domains, they are not a major focus of scientific interest.

Each protocol within the group of combined non-leading protocols was analyzed in detail to identify trends regarding the prospects of their research. The results are summarized in Table 3, and based on these data, a chart was created and presented as Figure 2.

Table 3

Annual number of publications on IoT non-leading communication protocols from 2011 to 2023 according to scopus

Year	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
AMQP	0	0	0	0	2	4	12	19	21	19	25	17	17
XMPP	2	5	3	2	7	6	14	17	13	12	16	9	10
DDS	0	0	1	1	5	8	10	10	9	10	7	9	10
OPC UA	0	0	2	0	1	3	5	8	12	14	16	16	8
LwM2M	0	0	0	0	6	3	4	11	7	9	8	5	9
STOMP	0	0	0	0	0	0	0	1	0	0	0	1	2
WAMP	0	0	0	0	0	1	0	0	0	0	0	0	0

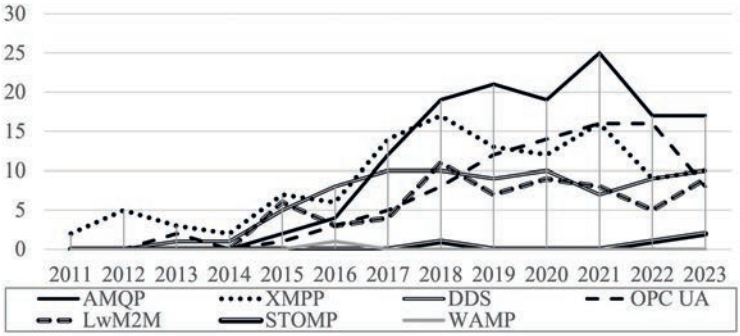

Fig. 2. Non-leading IoT protocols trends (2011–2023) based on data from Scopus

The analysis of the data indicates that, while some of the non-leading protocols attract a certain level of attention from researchers, they do not exhibit consistent and significant growth comparable to leading protocols such as MQTT or CoAP. This could be attributed to the narrow specialization of these protocols, their limited application areas, or competition from more popular and versatile technologies.

Conclusions. The conducted study revealed the significant dominance of the MQTT and CoAP protocols in the Internet of Things domain. MQTT

demonstrates a substantial advantage over other protocols in most use cases due to its features: message delivery control levels, client-broker architecture, encryption support, resilience to network quality and speed, comprehensive documentation, and low resource requirements for hardware. This is corroborated by the high level of interest within the scientific community, reflected in a significant number of publications and consistent growth in research activity.

The CoAP protocol also holds a significant position due to its resource efficiency and applicability in environments with limited device capabilities. Other protocols studied, such as AMQP, XMPP, DDS, OPC UA, LwM2M, STOMP, and WAMP, are primarily used in specific applications and do not demonstrate a high level of interest from the scientific community. This suggests that their usage is confined to certain niche areas where their unique features are essential.

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The CoAP protocol has proven effective in scenarios where resource efficiency is critical, and data loss is acceptable. By utilizing the UDP protocol, CoAP is more suitable for applications where packet loss may occur, such as streaming multimedia or sensor data transmission, where non-guaranteed delivery is acceptable. Further research could focus on optimizing CoAP for operation in unstable network conditions, as well as improving its reliability and security.

Other protocols, such as AMQP, XMPP, DDS, OPC UA, and LwM2M, hold potential for specialized applications. Prospects for further research include a deeper analysis of these protocols within the context of specific fields, such as industrial IoT, smart cities, or healthcare systems. Investigating their unique features and potential adaptation to the specific requirements of projects could facilitate more efficient use of these protocols and broaden their application scope.

Thus, future research may focus on developing combined approaches that integrate the advantages of various protocols to achieve optimal performance and efficiency in Internet of Things systems.

Список посилань / References

Al-Fuqaha, A., Guizani, M., Mohammadi, M., Aledhari, M., & Ayyash, M. (2015). Internet of Things: A survey on enabling technologies, protocols, and applications. *IEEE Communications Surveys & Tutorials*, *17*(4), 2347–2376. https://doi.org/10.1109/comst.2015.2444095. [In English].

Wytrębowicz, J., Cabaj, K., & Krawiec, J. (2021). Messaging Protocols for IoT Systems — A Pragmatic Comparison. *Sensors*, *21*(20), 6904. https://doi.org/10.3390/s21206904. [In English].

Scopus preview — Scopus — Welcome to Scopus. (n.d.). *Www.scopus.com*. https://www.scopus.com/search/form.uri?display=advanced. [In English].

MQTT specification. (n.d.-b). Retrieved November 17, 2024, from https://mqtt.org/mqtt-specification/. [In English].

COAP — Constrained Application Protocol | Specification. (n.d.). Retrieved November 17, 2024, from https://coap.space/spec.html. [In English].

AMQP 0-9-1 Protocol Specification | RabbitMQ. (n.d.). Retrieved November 17, 2024, from https://www.rabbitmq.com/amqp-0-9-1-protocol. [In English].

XMPP. (n.d.). Specifications. Retrieved November 17, 2024, from https://xmpp.org/extensions/. [In English].

About the Data Distribution Service Specification Version 1.4. (n.d.). Retrieved November 17, 2024, from https://www.omg.org/spec/DDS/1.4/About-DDS. [In English].

OPC UA Online Reference — Released specifications. (n.d.). Retrieved November 17, 2024, from https://reference.opcfoundation.org/. [In English].

Prado, J. (2019, April 18). Lightweight M2M (LWM2M). *OMA SpecWorks*. Retrieved November 17, 2024, from https://omaspecworks.org/what-is-oma-specworks/iot/lightweight-m2m-lwm2m/. [In English].

Protocol Specification — Web Application Messaging Protocol version 2 documentation. (n.d.). Retrieved November 17, 2024, from https://wamp-proto.org/spec.html. [In English].

Specification. (n.d.). STOMP. Retrieved November 17, 2024, from https://stomp.github.io/. [In English].

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