

EXPERIMENTAL EVALUATION OF COMMUNICATION PROTOCOLS ACROSS HETEROGENEOUS NETWORK INFRASTRUCTURES FOR M2M SENSOR DATA SYSTEMS USING THE AHP–TOPSIS MODEL

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Abstract: The selection of communication technologies and protocols in machine-to-machine (M2M) systems is a complex engineering task influenced by latency, reliability, throughput and deployment constraints. This paper presents an experimental evaluation of HTTP/1.1, HTTP/2, RabbitMQ and Apache Kafka using an integrated AHP–TOPSIS decision model across LAN, WLAN and hybrid KNX–IP environments. Performance is assessed through latency, message loss and throughput measurements. The results indicate that Apache Kafka offers the most balanced performance when reliability and scalability are prioritized, while demonstrating that protocol selection should consider both performance metrics and architectural characteristics. The study confirms the applicability of the AHP–TOPSIS methodology as a structured framework for communication protocol selection in M2M sensor data systems.

Key words: Internet of Things (IoT), M2M communication systems, network communication protocols, distributed sensor systems, multi-criteria decision analysis.

1. INTRODUCTION

Machine-to-machine (M2M) communication is a key component of modern Internet of Things (IoT) systems, enabling autonomous data exchange between distributed devices and information systems. As IoT deployments continue to expand, communication infrastructures must provide low latency, reliable message delivery, and efficient resource utilization to support continuous sensor data collection and processing [1,2].

Traditional fieldbus technologies such as KNX provide reliable low-latency communication in local environments but offer limited scalability and interoperability with modern distributed systems. Consequently, hybrid architectures combining fieldbus communication with IP-based networking have become increasingly common in industrial monitoring and building automation applications [3,4].

Communication technology selection in M2M systems cannot rely on a single performance metric. Instead, multiple criteria—including latency, reliability, and throughput—must be considered simultaneously, depending on the operational requirements of the target application. Previous studies have highlighted the importance of selecting communication technologies according to deployment conditions and workload characteristics [5–8].

To support such decisions, previous work proposed an integrated AHP–TOPSIS decision-support methodology for communication technology selection in M2M environments [9,10,12]. The present study extends its experimental validation to M2M sensor data collection systems by evaluating HTTP/1.1, HTTP/2, RabbitMQ, and Apache Kafka over wired LAN, wireless WLAN, and hybrid KNX–IP infrastructures [11].

The research investigates which IP-based communication technology provides the most balanced performance in terms of latency, reliability, and throughput under representative M2M deployment conditions. Empirical measurements are subsequently analysed using the AHP–TOPSIS framework to obtain a quantitative ranking of the evaluated technologies.

The remainder of the paper is organized as follows. Section 2 presents the decision-support methodology, Section 3 describes the experimental design, Section 4 presents the experimental results, while Sections 5 and 6 discuss the findings and conclude the paper.

2. RESEARCH METHODOLOGY

The proposed AHP–TOPSIS methodology is applied to evaluate communication technologies for M2M sensor data collection systems. The decision-support framework and its relationship to previous studies are briefly described in the following sections.

2.1. Relationship to Previous Work

This paper forms part of a broader research programme on the application of the AHP–TOPSIS methodology for communication technology selection in M2M environments. The proposed decision-support framework remains unchanged across the study, while its applicability is validated through experimental evaluations performed in different M2M application domains.

Previous studies [9, 10] investigated general communication protocol selection and real-time transactional data streaming systems. In contrast, the present work focuses on M2M sensor data collection over heterogeneous communication infrastructures, including wired LAN, wireless WLAN, and hybrid KNX–IP deployments. The primary contribution of this paper is the experimental validation of the proposed methodology under the operational requirements of sensor data collection systems, thereby extending its applicability to another representative M2M domain.

2.2. Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) is employed to determine the relative importance of the evaluation criteria used in the subsequent TOPSIS analysis. The

method derives criteria weights from pairwise comparisons, enabling domain-specific priorities to be incorporated into the decision-making process.

Let $C = \{c_1, c_2, \dots, c_n\}$ denote the set of evaluation criteria. Pairwise comparisons between the criteria are represented by a comparison matrix A :

$$A = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix} \quad (1)$$

where a_{ij} expresses the relative importance of criterion i over criterion j .

The normalized principal eigenvector of matrix A defines the weight vector:

$$W = (w_1, w_2, \dots, w_n) \quad (2)$$

where each weight w_i reflects the relative importance of the corresponding evaluation criterion.

The resulting weight vector is subsequently incorporated into the TOPSIS ranking procedure. For the sensor data collection domain considered in this study, higher priority is assigned to communication latency and delivery reliability than to throughput, reflecting the operational requirements of distributed monitoring systems.

2.3. TOPSIS Ranking Method

After the criteria weights are determined using AHP, the TOPSIS method is applied to rank the evaluated communication technologies. The method is based on the assumption that the optimal alternative should be located closest to the ideal solution and farthest from the anti-ideal solution.

Let $X = (x_{ij})$ denote the decision matrix, where x_{ij} represents the performance value of alternative i with respect to criterion j . The matrix is first normalized in order to ensure comparability between criteria with different units of measurement.

The normalized decision matrix is computed as

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}} \quad (3)$$

The weighted normalized matrix is then obtained by multiplying the normalized values with the corresponding AHP weights:

$$v_{ij} = w_j \cdot r_{ij} \quad (4)$$

Based on the weighted matrix, the ideal solution A^+ and the anti-ideal solution A^- are defined as

$$A^+ = \{\max(v_{ij}) \mid j \in J_{benefit}, \min(v_{ij}) \mid j \in J_{cost}\} \quad (5)$$

$$A^- = \{\min(v_{ij}) \mid j \in J_{benefit}, \max(v_{ij}) \mid j \in J_{cost}\} \quad (6)$$

The Euclidean distance of each alternative from the ideal and anti-ideal solutions is calculated as

$$S_i^+ = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^+)^2} \quad (7)$$

$$S_i^- = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2} \quad (8)$$

Finally, the closeness coefficient C_i is computed as

$$C_i = \frac{s_i^-}{s_i^+ + s_i^-} \quad (9)$$

The value of C_i ranges between 0 and 1. Higher values indicate alternatives that are closer to the ideal solution and therefore represent more suitable technological choices for the evaluated application domain. The obtained closeness coefficients are subsequently used to compare the evaluated communication technologies under identical experimental conditions.

2.4. Application of the Model

The integrated AHP–TOPSIS framework provides a systematic mechanism for evaluating communication technologies deployed over heterogeneous communication infrastructures. In the present study, the model is applied to compare HTTP/1.1, HTTP/2, RabbitMQ and Apache Kafka under LAN, WLAN and hybrid KNX–IP deployment scenarios representative of M2M sensor data collection systems. The evaluated technologies were selected because they represent fundamentally different communication paradigms, ranging from synchronous request–response communication to broker-based asynchronous messaging and distributed event streaming.

The resulting ranking provides a quantitative basis for selecting the most appropriate communication protocol under realistic deployment conditions.

2.5. Criteria Weights Derived Using AHP

The relative importance of the evaluation criteria was determined using the Analytic Hierarchy Process (AHP). The obtained weights reflect the priorities of the application domain considered in this study, namely M2M sensor data collection systems. In such environments, communication reliability and latency stability are typically more critical than raw throughput, since lost or delayed events may compromise the correctness of monitoring or control processes.

Based on pairwise comparison analysis, higher importance was assigned to latency-related metrics and message delivery reliability. Throughput remains relevant for evaluating system scalability, but it is considered secondary to the ability of the communication infrastructure to deliver events consistently and with predictable delays.

The resulting weight vector used in the TOPSIS evaluation is defined as

$$W = \{w_{L_{avg}} = 0.35, w_{L_{p99}} = 0.25, w_{Loss} = 0.20, w_{Tput} = 0.20\} \quad (10)$$

Here L_{avg} represents the average end-to-end latency, L_{p99} denotes the 99th percentile latency, $Loss$ corresponds to the percentage of lost messages, and $Tput$ represents the throughput measured in processed messages per second.

The higher weights assigned to latency metrics reflect the importance of stable and predictable response times in distributed sensor data systems, while the inclusion of throughput ensures that the evaluated technologies remain capable of supporting large-scale event streams.

3. EXPERIMENTAL DESIGN

The experimental evaluation investigates the performance of representative communication technologies for M2M sensor data collection under heterogeneous

deployment conditions. The resulting measurements provide the empirical input for the proposed AHP–TOPSIS decision-support model.

3.1. Motivation and Research Hypothesis

The objective of the experimental evaluation is to assess the performance of HTTP/1.1, HTTP/2, RabbitMQ, and Apache Kafka across representative M2M sensor data collection environments. The resulting measurements provide the empirical input for the AHP–TOPSIS decision-support model presented in Section 2.

The research hypothesis is that the relative suitability of communication technologies depends on both deployment conditions and application-specific performance requirements rather than on any single performance metric.

3.2. Selection of Communication Technologies

HTTP/1.1, HTTP/2, RabbitMQ, and Apache Kafka were selected because they represent the principal communication paradigms used in contemporary M2M systems, including synchronous request–response communication, asynchronous message-oriented middleware, and distributed event streaming. In all IP-based configurations, Raspberry Pi platforms equipped with KNX HAT interfaces act as protocol gateways, enabling the technologies to be evaluated under identical experimental conditions representative of heterogeneous M2M sensor data collection environments.

3.3. Experimental Architecture

Three representative deployment architectures were implemented to evaluate the communication technologies under different M2M sensor data collection environments. Across all experiments, identical sensing devices, hardware platforms, application logic, message structure, workload profiles, and performance metrics were preserved, while only the communication technology was varied.

1. **Wired KNX-IP Deployment (LAN).** In this configuration (Figure 1), communication is performed through a stable wired network based on Gigabit Ethernet. The wired LAN deployment serves as the reference scenario in which protocol performance is evaluated under stable network conditions with negligible transmission variability.

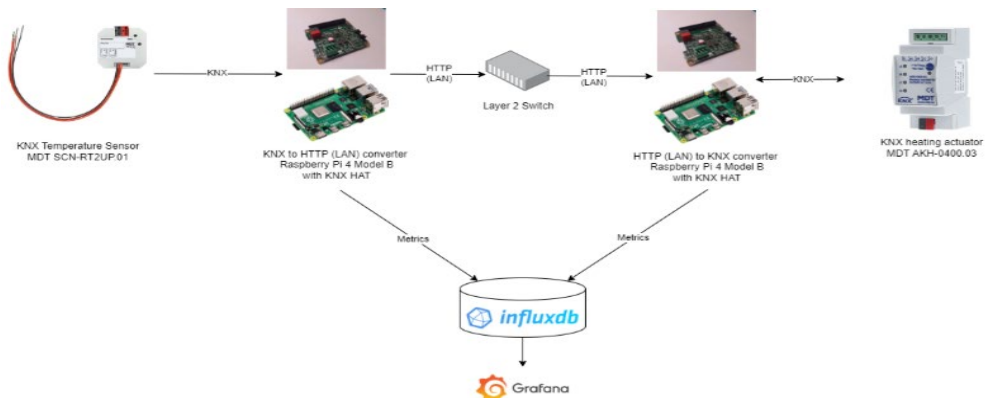


Figure 1. Experimental deployment architecture using KNX over wired LAN.

2. Wireless KNX-IP Deployment (WLAN). The second configuration (Figure 2) uses a wireless network based on IEEE 802.11n. This environment introduces variability in network latency and packet loss, simulating conditions commonly found in large building installations or environments with wireless infrastructure constraints. The comparison between the LAN and WLAN configurations enables assessment of the robustness of each communication technology under varying network conditions.

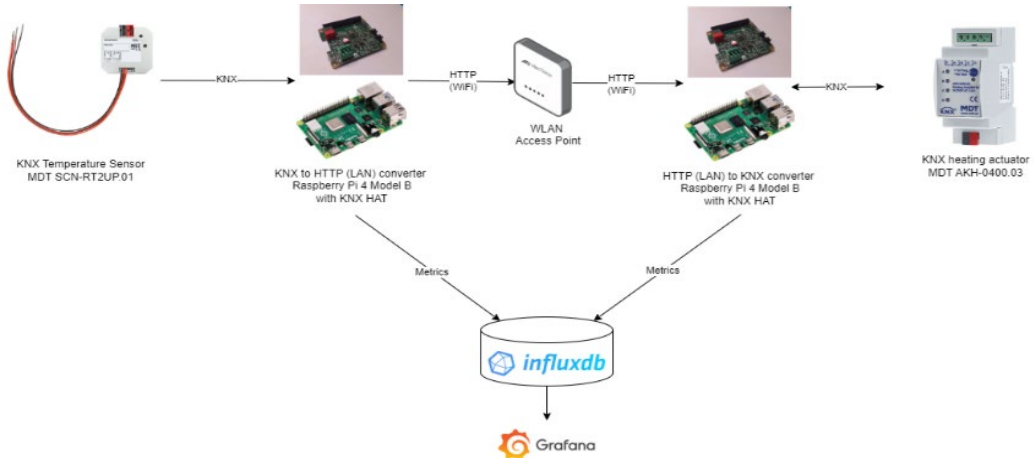


Figure 2. Experimental deployment architecture using KNX over WLAN.

3. Native KNX Communication (Benchmark). A direct KNX communication scenario (Figure 3) is used as the benchmark reference. The benchmark configuration represents native KNX fieldbus communication without introducing additional IP networking or middleware layers. The obtained measurements serve as a reference for estimating the communication overhead introduced by the evaluated IP-based technologies.

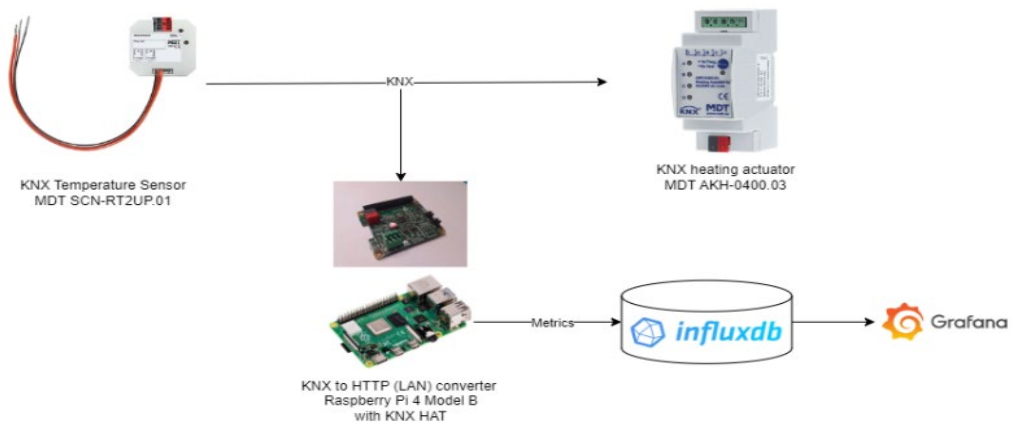


Figure 3. Native KNX benchmark architecture.

System metrics are collected using InfluxDB and visualized through Grafana. The measurements obtained from the three deployment scenarios constitute the empirical decision matrix used by the AHP–TOPSIS evaluation model.

3.4. Experimental Infrastructure

All experiments were performed using identical hardware, software, application logic, and message structures. KNX-compatible sensors and Raspberry Pi gateways equipped with KNX HAT interfaces were used throughout the experiments, while only the evaluated communication technology was varied. Performance metrics were collected using InfluxDB and analysed through Grafana, ensuring a controlled and reproducible experimental environment.

3.5. Workload Generation

The experimental workload combines periodic measurements generated by a physical KNX temperature sensor with a configurable synthetic workload generator used to emulate increased sensor traffic. This approach enables evaluation of the communication technologies under both normal operating conditions and controlled high-load scenarios.

Each generated message contains a unique trace identifier, sequence number, timestamp, sensor identifier, and measurement value, enabling end-to-end message correlation together with verification of message ordering and loss.

The same workload was executed for all evaluated communication technologies and deployment scenarios, ensuring fair and reproducible comparison. The collected measurements constitute the empirical input for the AHP–TOPSIS evaluation presented in Section 4.

3.6. Performance Metrics

Communication performance was evaluated using four quantitative metrics selected as input to the AHP–TOPSIS decision-support model:

- Average end-to-end latency (L_{avg}) – average message delivery time from the sensing device to the receiving application.
- 99th percentile latency (L_{p99}) – worst-case communication delay under sustained operation.
- Message loss (Loss) – percentage of generated messages that failed to reach the destination.
- Throughput (T_{put}) – number of successfully processed sensor messages per second.

Together, these metrics characterize communication responsiveness, reliability, and scalability under representative M2M sensor data collection conditions.

3.7. Measurement Methodology

A unified measurement methodology was applied throughout all experiments. Each sensor message was augmented with a unique trace identifier, sequence number, and UTC timestamp, enabling end-to-end correlation across the communication infrastructure.

Communication latency was determined from timestamp measurements recorded at predefined processing stages. The overall end-to-end latency, network transmission latency, and gateway processing overhead were calculated as

$$L_{E2E} = t_3 - t_1 \quad (11)$$

$$L_{net} = t_3 - t_2 \quad (12)$$

$$L_{conv} = (t_2 - t_1) + (t_4 - t_3) \quad (13)$$

Message counters recorded at the sender, gateway, and receiver were used to determine message delivery and calculate message loss. All measurements were stored in InfluxDB and analysed using Grafana dashboards. Time synchronization between all participating nodes was maintained using Chrony operating in UTC.

4. EMPIRICAL RESULTS AND TOPSIS ANALYSIS

This section presents the empirical results obtained from the experimental evaluation and the subsequent application of the TOPSIS ranking method. The measured performance metrics are first summarized, followed by the normalization process and the computation of weighted decision values. The final ranking of the evaluated communication technologies is obtained using the closeness coefficient derived from the TOPSIS model.

4.1. Empirical Results

The experimental measurements collected from the LAN and WLAN environments under controlled workload conditions are summarized in Table 3. The results include average latency, tail latency (99th percentile), percentage of lost messages, and system throughput.

Table 3. Empirical Performance Results Obtained from the Experiments

Protocol / Environment	L_{avg} (ms)	L_{p99} (ms)	Loss (%)	T_{put} (msg/s)
KNX (benchmark)	4.3	6.8	0.09	220
HTTP/1.1 (LAN)	35.7	82.5	0.16	980
HTTP/2 (LAN)	22.4	45.9	0.12	1360
RabbitMQ (LAN)	28.2	60.4	0.08	1520
Apache Kafka (LAN)	41.3	85.1	0.05	2100
HTTP/1.1 (WLAN)	57.6	132.8	0.58	710
HTTP/2 (WLAN)	39.9	96.3	0.42	880
RabbitMQ (WLAN)	46.7	108.2	0.35	960
Apache Kafka (WLAN)	64.8	145.7	0.29	1400

The reported measurements constitute the empirical decision matrix used as input to the AHP–TOPSIS evaluation framework described in Section 2.

4.2. Data Normalization

In order to enable comparison between criteria with different measurement units, the empirical results are normalized using the standard TOPSIS normalization procedure. Latency and message loss are treated as cost criteria, while throughput represents a benefit criterion.

The normalized decision matrix $R = (r_{ij})$ is obtained using the normalization formula defined in the methodology section. The resulting normalized values are presented in Table 4.

Table 4. Normalized Decision Matrix

<i>Protocol / Environment</i>	<i>L_{avg}</i>	<i>L_{p99}</i>	<i>Loss</i>	<i>T_{put}</i>
<i>KNX (benchmark)</i>	<i>1.000</i>	<i>1.000</i>	<i>0.094</i>	<i>0.073</i>
<i>HTTP/1.1 (LAN)</i>	<i>0.120</i>	<i>0.082</i>	<i>0.053</i>	<i>0.467</i>
<i>HTTP/2 (LAN)</i>	<i>0.192</i>	<i>0.149</i>	<i>0.071</i>	<i>0.649</i>
<i>RabbitMQ (LAN)</i>	<i>0.153</i>	<i>0.113</i>	<i>0.107</i>	<i>0.725</i>
<i>Apache Kafka (LAN)</i>	<i>0.104</i>	<i>0.080</i>	<i>0.171</i>	<i>1.000</i>
<i>HTTP/1.1 (WLAN)</i>	<i>0.075</i>	<i>0.051</i>	<i>0.015</i>	<i>0.338</i>
<i>HTTP/2 (WLAN)</i>	<i>0.108</i>	<i>0.070</i>	<i>0.021</i>	<i>0.420</i>
<i>RabbitMQ (WLAN)</i>	<i>0.092</i>	<i>0.062</i>	<i>0.025</i>	<i>0.458</i>
<i>Apache Kafka (WLAN)</i>	<i>0.066</i>	<i>0.047</i>	<i>0.030</i>	<i>0.667</i>

4.3. Weighted Decision Matrix

The normalized values are multiplied by the weights obtained from the AHP analysis in order to produce the weighted decision matrix $V = (v_{ij})$. The applied weight vector is defined as

$$W = \{0.35, 0.25, 0.20, 0.20\} \quad (14)$$

The resulting weighted matrix is presented in Table 5.

Table 5. Weighted Decision Matrix

<i>Protocol / Environment</i>	<i>L_{avg}</i>	<i>L_{p99}</i>	<i>Loss</i>	<i>T_{put}</i>
<i>KNX (benchmark)</i>	<i>0.350</i>	<i>0.250</i>	<i>0.019</i>	<i>0.015</i>
<i>HTTP/1.1 (LAN)</i>	<i>0.042</i>	<i>0.021</i>	<i>0.011</i>	<i>0.093</i>
<i>HTTP/2 (LAN)</i>	<i>0.067</i>	<i>0.037</i>	<i>0.014</i>	<i>0.130</i>
<i>RabbitMQ (LAN)</i>	<i>0.054</i>	<i>0.028</i>	<i>0.021</i>	<i>0.145</i>
<i>Apache Kafka (LAN)</i>	<i>0.036</i>	<i>0.020</i>	<i>0.034</i>	<i>0.200</i>
<i>HTTP/1.1 (WLAN)</i>	<i>0.026</i>	<i>0.013</i>	<i>0.003</i>	<i>0.068</i>
<i>HTTP/2 (WLAN)</i>	<i>0.038</i>	<i>0.018</i>	<i>0.004</i>	<i>0.084</i>
<i>RabbitMQ (WLAN)</i>	<i>0.032</i>	<i>0.016</i>	<i>0.005</i>	<i>0.092</i>
<i>Apache Kafka (WLAN)</i>	<i>0.023</i>	<i>0.012</i>	<i>0.006</i>	<i>0.133</i>

4.4. Ideal and Anti-Ideal Solutions

The ideal solution A^+ and the anti-ideal solution A^- are determined by selecting the maximum and minimum values from each column of the weighted matrix depending on the criterion type (Table 6).

Table 6. Ideal and Anti-Ideal Solutions

<i>Criterion</i>	<i>Ideal (A^+)</i>	<i>Anti-Ideal (A^-)</i>
L_{avg}	0.350 (KNX)	0.023 (Kafka WLAN)
L_{p99}	0.250 (KNX)	0.012 (Kafka WLAN)
$Loss$	0.034 (Kafka LAN)	0.003 (HTTP/1.1 WLAN)
T_{put}	0.200 (Kafka LAN)	0.015 (KNX)

4.5. Distance Calculation and Closeness Coefficient

The Euclidean distances to the ideal and anti-ideal solutions are computed for each evaluated alternative. The resulting closeness coefficient C_i represents the relative proximity of each alternative to the ideal solution (Table 7).

Table 7. TOPSIS Distance and Ranking Results

<i>Protocol / Environment</i>	S^+	S^-	C_i	<i>Rank</i>
KNX (benchmark)	0.030	0.340	0.92	1
Apache Kafka (LAN)	0.080	0.215	0.73	2
RabbitMQ (LAN)	0.098	0.183	0.65	3
HTTP/2 (LAN)	0.110	0.164	0.60	4
Apache Kafka (WLAN)	0.127	0.123	0.49	5
RabbitMQ (WLAN)	0.138	0.109	0.44	6
HTTP/2 (WLAN)	0.144	0.100	0.41	7
HTTP/1.1 (LAN)	0.155	0.086	0.36	8
HTTP/1.1 (WLAN)	0.178	0.071	0.28	9

The obtained ranking reflects the application-specific priorities defined through the AHP weighting procedure. Although native KNX communication achieves the highest overall score, it serves primarily as a benchmark configuration. Among the evaluated IP-based technologies, Apache Kafka achieves the highest ranking, followed by RabbitMQ and HTTP/2. The results further confirm that communication technology selection depends on application-specific evaluation criteria and their relative importance.

5. DISCUSSION

The experimental results demonstrate that communication technology selection in M2M sensor data collection systems depend on multiple performance criteria rather than on a single indicator. Although all evaluated technologies successfully support sensor

communication, significant differences were observed in latency, reliability, and throughput under different deployment conditions. These differences justify the application of the AHP–TOPSIS decision-support methodology.

The primary contribution of this study is the experimental validation of the proposed AHP–TOPSIS methodology in a new application domain. While previous studies [9,10,12] investigated general communication protocol selection and real-time transactional data streaming systems, the present work applies the same methodological framework to M2M sensor data collection over heterogeneous LAN, WLAN, and KNX–IP infrastructures. The results demonstrate that the methodology can be consistently applied across different M2M domains while adapting the evaluation criteria and their relative importance to application-specific requirements.

The experiments further show that deployment conditions substantially influence communication performance. Native KNX communication provides the lowest latency, whereas IP-based deployments introduce additional protocol and network overhead. The comparison between LAN and WLAN environments also highlights the impact of wireless communication on latency and message loss, indicating that technology selection should consider both protocol characteristics and deployment infrastructure.

Taken together with the previous studies [9,10,12], the present work provides additional evidence supporting the general applicability of the proposed AHP–TOPSIS methodology for communication technology selection in representative M2M application domains.

6. CONCLUSIONS

This study experimentally evaluated HTTP/1.1, HTTP/2, RabbitMQ, and Apache Kafka for M2M sensor data collection over LAN, WLAN, and hybrid KNX–IP infrastructures using an integrated AHP–TOPSIS decision-support framework.

The results demonstrate that communication technology selection should consider multiple performance criteria rather than latency alone. Although native KNX provides the lowest communication latency, Apache Kafka achieves the highest ranking among the evaluated IP-based technologies, followed by RabbitMQ. The experiments also confirm the influence of deployment conditions, with WLAN introducing higher latency and message loss than wired LAN environments.

The proposed AHP–TOPSIS methodology provides a systematic and reproducible framework for communication technology selection in M2M sensor data collection systems. Together with the previously published studies [9,10,12], the present work extends the experimental validation of the methodology to another representative M2M application domain.

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