Multi-Criteria Decision Making Approaches for Choice of Wireless Communication Technologies for IoT-Based Systems

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Abstract. In this paper, several methods and approaches for multi-criteria selection of wireless communication technologies for Internet of Things (IoT) systems are analyzed. Their comparative analysis allows to choose the most appropriate multi-criteria method for increasing the efficiency of decision-making for different input data and various functioning conditions of IoT-based systems. The multi-criteria task of choosing a wireless communication technologies is definitely complicated and important because the decision-making process can be influenced by various types of criteria. Authors discuss in detail the simulation results and advantages of multi-criteria selection of wireless communication technologies based on the methods of linear, Max-Min and multiplicative convolution and the ideal point method with different metrics (Euclidean, Hamming and Chebyshev) with the study of the influence of current methods on the decision making efficiency.

Keywords: wireless communication technology, IoT, decision-making, multi-criteria approach, ideal point method.

1 Introduction

Decision-making always involves choosing one of the possible options making decisions. These possible options are called alternatives. Problem situations must have at least two options. That is, at least two alternatives are needed to create a decision-making task. Independent alternatives are alternatives, actions which do not affect the quality of other alternatives. Dependent alternatives are decisions on one of them affect the other [1-3].

Sometimes all alternatives are given in advance and you just have to select from them. The peculiarity of such tasks lies in a closed and non-expanded number of alternatives. But there are tasks in which all alternatives or part of them are not formed before the decision is made. Often on the basis of such alternatives in the process of selection, new alternatives or a set of requirements to existing alternatives arise. This task class calls tasks with constructive alternatives [1].

When there are many alternatives, the decision maker (DM) cannot devote enough time and attention to analyze each of them. So there is a need for tools to support choosing (making) decisions. In the modern decision-making theory, it is considered that variants of solutions are characterized by various types of their attractiveness for DM [1, 2, 4]. These indicators are called attributes, factors or quality metrics. All of them serve as criteria for choosing a solution. The number of criteria are usually more than one in different theoretical constructions and decision methods. Modern methods of decision-making take into account all the special qualities of alternatives that significantly brings formal schemes to the real world. Therefore, now a multi-criteria description is becoming more popular in use. Usually, evaluation criteria are not given at the beginning of the analysis of the problem. They are established by DM and experts [1].

2 Related Works and Problem Statement

Recently, wireless data transmission has become increasingly popular. The widespread use of wireless networks is due to the fact that they can be used not only on personal computers, but also on phones, tablets and laptops, at a reasonable price, convenience and provide sufficient data transfer speeds for most applications. The main advantage of wireless networks is the permission to implement a network project in the short term and reduce the cost of creating a system [5, 6].

The task of choosing a wireless data transfer (communication) technology is definitely relevant as the decision-making process can be influenced by various types of criteria, in particular, the quality and power of the data signal, the security of the technology, energy efficiency, etc. In most cases, the choice of wireless data technology is reduced to a comparative analysis of their capabilities and pricing policies. In this case, IoT developers often prefer well-known wireless data technologies, without taking into account the criteria (factors) that may affect the development, maintenance, updating, reliability, security and scaling of developed IoT systems in the future. Incorrectly selected technology can lead to various losses [5, 7, 8].

Let's consider several wireless communication technologies: ZigBee (E_1), Wi-Fi (E_2), Bluetooth (E_3), Z-Wave (E_4), WiMAX (E_5), Classic WaveLAN (E_6). Each of these technologies has its advantages and disadvantages.

ZigBee (E_1) technology for wireless sensory and personal networks. The ZigBee technology provides low power consumption and data transfer at a non-licensed 2.4 GHz frequency (different countries may vary in frequency) up to 250 KB / s, up to 75 meters in direct line of sight. One of the advantages and disadvantages of technology at the same time is its complexity [9, 10].

Wi-Fi (E_2) is a trademark of the Wi-Fi Alliance association, which is a standard set of standards for IEEE 802.11 for broadband radio communications. Depending on the standard, Wi-Fi uses a data bandwidth of 2.4 GHz or 5 GHz. The main disadvantage of Wi-Fi compared with competitors is relatively higher power consumption [5, 11, 12].

Bluetooth (E_3) low-bandwidth radio communication technology (typically up to 200 meters) in the unlicensed frequency band (ISM range: 2.4-2.4835 GHz). One of the easiest ways to connect two devices. To communicate between devices, only a Bluetooth adapter is required. Relative versatility is both an advantage and a lack of Bluetooth [6, 13-15].

Z-Wave (E_4) is a compatible wireless technology for managing and monitoring applications for residential and commercial environments [4]. The main purpose of Z - Wave is to provide reliable transmission of short messages from the control unit to other network nodes [10]. The Z-Wave network allows you to use the full-type topology without the need for a coordinator [5, 17, 18].

LTE (E_5) is a standard for wireless broadband communication, based on the GSM/EDGE and UMTS/HSPA technologies. It increases the capacity and speed using a different radio interface together with core network improvements. Its main features are peak download rates up to 299.6 Mbit/s and upload rates up to 75.4 Mbit/s depending on the user equipment category (with 4×4 antennas using 20 MHz of spectrum); five different terminal classes have been defined from a voice-centric class up to a high-end terminal that supports the peak data rates; all terminals will be able to process 20 MHz bandwidth; support of at least 200 active data clients in every 5 MHz cell [5, 6, 10].

Classic WaveLAN (E_6) is used to organize local networks (a wireless alternative to wired networks Ethernet and Token Ring). Data transmission is carried out in the frequency range of 900 MHz or 2.4 GHz, while the transmission speed is up to 2 Mbps [19-21].

The following criteria for choosing a wireless data technology were selected.

Data transfer rate (Q_1). The average number of bits, characters, or units transmitted per unit time between two corresponding data transfer system devices [5].

Frequency Range (Q_2). Frequency band limited by certain values [6].

Technology Definition (Q_3). Alert for unauthorized access or damage to IoT devices using a wireless network [8, 10].

Number of nodes (Q_4). The typical wireless network infrastructure consists of several access nodes. These nodes are connected to the network by means of wires and form the hidden-minded users of cities for wireless clients. Wireless clients are client devices (say, laptops, desktops, or pocket computers) [5, 11].

Range of action (Q_5). Maximum distance between transmitter and receiver [10].

Energy Efficiency (Q_6). Effective (rational) use of energy reserves. Wireless sensor networks can be used to monitor energy efficiency [13].

The multi-criteria problem can be formulated on the basis of developed criteria and a set of alternative solutions, and can be solved by one of the appropriate methods of multi-acceptance of pinning, in particular by the methods of coagulation (linear, Max-Min, multiplicative) and the ideal point method [1-3, 22, 23].

3 Methods of Multi-criteria Selection of Wireless Communication Technology

The analysis of many real practical problems naturally led to the emergence of a class of multi-criteria problems. The solution of the corresponding problems is through the use of such methods as selection of the main criterion, linear, multiplicative and Max-Min convolutions, the ideal point method, the method of sequential concessions, lexicographic optimization. Most of the methods of multi-criteria decision-making provide a multi-criteria problem for a one-tiered one, which greatly simplifies the decision-making process [1, 24-26].

The task of choosing a wireless data technology can be presented in the following form (decision matrix):

$$Q(E_i) = \begin{pmatrix} Q_1(E_1) & Q_1(E_2) & \dots & Q_1(E_m) \\ Q_2(E_1) & Q_2(E_2) & \dots & Q_2(E_m) \\ \dots & \dots & & \dots \\ Q_n(E_1) & Q_n(E_2) & \dots & Q_n(E_m) \end{pmatrix}; E_i \in E; (i = 1, 2, \dots, m; j = 1, 2, \dots, n), \quad (1)$$

where $Q(E_i)$ is the vector criterion of quality of the *i*-th alternative; $Q_j(E_i)$ is the *j*-th component of the vector criterion of quality $Q(E_i)$.

The evaluation of the *i*-th alternative for the *j*-th criterion $Q_j(E_i)$ has a well-defined scale of evaluation and is formed by experts based on their experience, knowledge and experimental research in the field of wireless data transfer technology between devices in IoT networks [1-3, 25, 27].

To solve the problem of choosing a wireless data technology, you need to find the best alternative E^* based on the input data (1):

$$E^* = Arg \max_{i=1,2,\dots,m} \left(Q(E_i) \right), E_i \in E; i = 1, 2, ..., 6 . \quad (2)$$

All methods for solving multi-criteria optimization problems are based on the construction of an initial problem with a vector criterion to an optimization problem with a scalar criterion. The methods themselves differ only by the mechanism of realization of such an assembly. Let's consider the convolution methods: linear, max-min, and multiplicative of partial criteria [1, 3, 27-29].

The simplest and most widespread way of combining the original criteria is based on the use of a linear convolution that has the form [1, 30]:

$$Q(E_i) = \sum_{j=1}^{n} \omega_j Q_j(E_i) \Rightarrow Max; E_i \in E; \omega_j > 0; \sum_{j=1}^{n} \omega_j = 1; i = 1, 2, \dots, m , \quad (3)$$

where ω_j is the weight coefficient reflecting the relative importance of the *j*-th criterion $Q_j(E_i)$.

Most methods of multi-criteria decision-making are based precisely on the application of this method. The reasons for this are the simplicity and visibility of the method. Weights can be considered as indicators of the relative importance of each criterion [1, 25, 29, 30].

More versatile, from the point of view of the application area is the Max-Min convolution, which has the form [1, 25]:

$$Q(E_i) = \min_{i=1,2,\dots,m} \omega_j Q_j(E_i) \Rightarrow Max; E_i \in E; \omega_j > 0; \sum_{j=1}^{n} \omega_j = 1. \quad (4)$$

Another variant of the scalarization of the criteria is the multiplicative convolution [1, 3, 25, 30]:

$$Q(E_i) = \prod_{j=1}^{n} \left(Q_j(E_i)\right)^{\omega_j} \Rightarrow Max; E_i \in E; \omega_j > 0; \sum_{j=1}^{n} \omega_j = 1; i = 1, 2, \dots, m. \quad (5)$$

In this case, the main feature of the application of these methods is the choice of a method for the formation of weight coefficients ω_j. This significantly influences the choice of the optimal solution E^* [30-32].

The name of the method of an ideal point is due to the fact that when it implements, the DM specifies certain target values for each partial criterion. Within the framework of the method, the assumption is made that the so-called "ideal point" exists in the space of the criteria [1, 3, 30]:

$$Q_j^* \Rightarrow \max_{i \in \{1,2,\dots,m\}} Q_j(E_i); E_i \in E; i = 1, 2, \dots m; j = 1, 2, \dots n, \quad (6)$$

where Q_j^* is the optimal solution of the *j*-th criterion.

These optimal solutions will serve as coordinates of the ideal point in the criteria space [1, 30]:

$$Q^* = \left(Q_1^*, Q_2^*, \dots, Q_n^*\right), \quad (7)$$

where Q^* is an ideal point.

If the ideal point is permissible (but this happens very rarely), the decision is considered to be received. Otherwise, it is necessary to determine the distance to the ideal point. To do this, you need to select a metric, and finally solve one criterion problem of finding a point from the set of permissible solutions, which is closest to the ideal [1]. The optimization task looks like this:

$$d_p(E_i) = p\left(Q(E_i) - Q^*\right) \Rightarrow Min; E_i \in E; i = 1, 2, \dots m, \quad (8)$$

where $d_p(E_i)$ is the distance between the ideal point and the *i*-th alternative $Q(E_i)$; p is the metric of distance measurement.

If the Euclidean metric is chosen, then distance (8) has the form [1]:

$$d_p\left(E_i\right)=\sqrt{\sum_{j=1}^{n}\left(Q_j\left(E_i\right)-Q_j^*\right)^2}\Rightarrow Min; E_i\in E; i=1,2,\ldots m, j=1,2,\ldots n. \quad (9)$$

If the Heming Metric is selected, then distance (8) has the form [1, 4]:

$$d_p\left(E_i\right)=\sum_{j=1}^{n}\left|Q_j\left(E_i\right)-Q_j^*\right|\Rightarrow Min; E_i\in E; i=1,2,\ldots m, j=1,2,\ldots n. \quad (10)$$

If the Chebyshev metric is chosen, then distance (8) has the form [1, 30]:

$$d_p\left(E_i\right)=\max_{i=1,2,\ldots,m}\left|Q_j\left(E_i\right)-Q_j^*\right|\Rightarrow Min; E_i\in E; i=1,2,\ldots m, j=1,2,\ldots n. \quad (11)$$

4 An Example of Multi-criteria Choice of Wireless Communication Technology Using Convolution Methods and Ideal Point Method

Experts are encouraged to evaluate alternative solutions according to the indicated criteria using the 10-point rating scale (from 1 to 10), where 10 points correspond to the largest (better) value of the alternative solution by the criterion [30]. Consider an example of expert assessments for this task in Table 1.

For this example, we use the direct evaluation method, that is, the expert himself determines the importance of each criterion. Table 2 shows the weight coefficients for each criterion using simple ranking method [1, 30].

Table 1. The decision matrix for the choice of wireless communication technology

	E_1	E_2	E_3	E_4	E_5	E_6
Q_1	6	9	8	9	10	8
Q_2	8	8	7	9	8	6
Q_3	7	8	6	8	6	7
Q_4	9	4	9	7	7	9
Q_5	10	7	8	5	8	6
Q_6	8	9	4	8	10	9

Table 2. Weight coefficients (ω_j) of criteria

	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6
ω_j	0.28	0.22	0.22	0.07	0.14	0.07

Calculate with a linear convolution method (3):

$$
\begin{aligned}
&Q(E_1) = 6\cdot 0.28 + 8\cdot 0.22 + 7\cdot 0.22 + 9\cdot 0.07 + 10\cdot 0.14 + 8\cdot 0.07 = 7.57;\\
&Q(E_2) = 9\cdot 0.28 + 8\cdot 0.22 + 8\cdot 0.22 + 4\cdot 0.07 + 7\cdot 0.14 + 9\cdot 0.07 = 7.93;\\
&Q(E_3) = 8\cdot 0.28 + 7\cdot 0.22 + 6\cdot 0.22 + 9\cdot 0.07 + 8\cdot 0.14 + 4\cdot 0.07 = 7.13;\\
&Q(E_4) = 9\cdot 0.28 + 9\cdot 0.22 + 8\cdot 0.22 + 7\cdot 0.07 + 5\cdot 0.14 + 8\cdot 0.07 = 8.01;\\
&Q(E_5) = 10\cdot 0.28 + 8\cdot 0.22 + 6\cdot 0.22 + 7\cdot 0.07 + 8\cdot 0.14 + 10\cdot 0.07 = 8.19;\\
&Q(E_6) = 8\cdot 0.28 + 6\cdot 0.22 + 7\cdot 0.22 + 9\cdot 0.07 + 6\cdot 0.14 + 9\cdot 0.07 = 7.2.
\end{aligned}
\tag{12}
$$

In this way (12), the best alternative is E_5 (LTE).

Calculate with Max-Min convolution (4). In this case (Table 3), the best alternative is E_6 (Classic WaveLAN).

Table 3. Results of using Max-Min convolution

	E_1	E_2	E_3	E_4	E_5	E_6
$Q(E_i)$	0.56	0.28	0.28	0.49	0.49	0.63

Calculate using multiplicative convolution (5). In this case (Table 4), the best alternative is E_5 (LTE).

$$
\begin{aligned}
&Q(E_1) = 6^{0.28}\cdot 8^{0.22}\cdot 7^{0.22}\cdot 9^{0.07}\cdot 10^{0.14}\cdot 8^{0.07} = 7.46;\\
&Q(E_2) = 9^{0.28}\cdot 8^{0.22}\cdot 8^{0.22}\cdot 4^{0.07}\cdot 7^{0.14}\cdot 9^{0.07} = 7.79;\\
&Q(E_3) = 8^{0.28}\cdot 7^{0.22}\cdot 6^{0.22}\cdot 9^{0.07}\cdot 8^{0.14}\cdot 4^{0.07} = 7.0;\\
&Q(E_4) = 9^{0.28}\cdot 9^{0.22}\cdot 8^{0.22}\cdot 7^{0.07}\cdot 5^{0.14}\cdot 8^{0.07} = 7.87;\\
&Q(E_5) = 10^{0.28}\cdot 8^{0.22}\cdot 6^{0.22}\cdot 7^{0.07}\cdot 8^{0.14}\cdot 10^{0.07} = 8.04;\\
&Q(E_6) = 8^{0.28}\cdot 6^{0.22}\cdot 7^{0.22}\cdot 9^{0.07}\cdot 6^{0.14}\cdot 9^{0.07} = 7.12.
\end{aligned}
\tag{13}
$$

Calculate using ideal point method. Find the coordinates of the ideal point as the maximum values (6) of all the criteria.

Consequently, the ideal point (7) in the criterion space has the following coordinates:

$$Q^* = (Q_1^*, Q_2^*, Q_3^*, Q_4^*, Q_5^*, Q_6^*) = (10, 9, 8, 9, 10, 10).$$

The ideal point is not equivalent to any of the alternative solutions; therefore, it is necessary to find the distance between the alternatives and the ideal point (8) using the different metrics. An alternative with the smallest distance will be optimal.

Calculate the distance using the Euclidean metric (9) from the E_1 to Q^*:

$$d_p(E_1) = \sqrt{(6-10)^2 + (8-9)^2 + (7-8)^2 + (9-9)^2 + (10-10)^2 + (8-10)^2} = 4,69.$$

Calculate the distance using the Heming metric (10) from the E_1 to Q^*:

$$d_p(E_1) = |6-10| + |8-9| + |7-8| + |9-9| + |10-10| + |8-10| = 8.0 .$$

Calculate the distance using the Chebyshev Metric (11) from the E_1 to Q^*:

$$d_p(E_1) = Max(|6-10|, |8-9|, |7-8|, |9-9|, |10-10|, |8-10|) = 4.0 .$$

The distances for all alternatives are given in Table 4.

Table 3. Comparison of the distances for all alternatives based on the metrics of Euclidean, Haming and Chebyshev

	E_1	E_2	E_3	E_4	E_5	E_6
Euclidean metric	4.69	6.08	7.21	5.83	3.61	5.57
Heming metric	8	11	14	10	7	11
Chebyshev metric	4	5	6	5	2	4

According to Table 3 the minimum distances are 3.61, 7 and 2. All indicators refer to the alternative E_5 (LTE).

So, the results by the convolution methods (3), (4), (5) and the ideal point method with different metrics (9), (10), (11) lead to the optimal alternative E_5 (LTE).

5 Conclusions

Nowadays, there are many varieties of wireless communication technologies, both in terms of typology and in terms of their personal capabilities, characteristics. There is a problem of rational choice of technology for a certain IoT system taking into account the criteria (factors) that affect the result of the evaluation. This technique avoids various losses in the subsequent work of the IoT system due to improperly chosen technology.

In this paper, such methods as linear, Max-Min, and multiplicative convolutions and the ideal point method with different metrics (Euclidean, Hamming and Chebyshev) were considered.

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