

# Multi-Criteria Selection of the Wireless Communication Technology for Specialized IoT Network

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**Abstract.** The task of the selection of the appropriate wireless communication technology (WCT) in the IoT network is very relevant today. The complexity of the selection process is due to the large number of existing WCTs, which are available on the IoT communications market, and the variety of their features, possibilities and spheres of applications. In this paper, the multi-criteria decision making approach for choosing the WCT (data transfer technology) within designing IoT systems is considered. For solving multi-criteria decision making problem, authors use the ideal point method with different metrics to calculate the distance between alternatives. Special attention is paid to the impact analysis of various metrics on the results of the WCT selection. The reliability, dependability, safety and security of IoT systems are considered as the most important criteria for decision making in WCT selection processes. Special cases of choosing the WCT in the IoT network with confirmation of the appropriateness of the using proposed approach are discussed.

**Keywords:** wireless communication technology, IoT network, reliability, safety, multi-criteria decision making.

## 1 Introduction

Decision making always involves selecting one of the possible variants of decisions. These possible variants of decisions are called alternatives. For the problem of selecting decisions it is necessary to have at least two alternatives. When there are many alternatives, a decision maker (DM) cannot take enough time and attention to analyze each of them, so there is a need for means to support the choice of decisions. There is also a need of such facilities when the number of alternatives is small. In such problems, the number of alternatives, from the consideration of which the choice begins, is relatively small. But they are not the only ones possible. Often, on their basis, new alternatives arise during the selection process. Primary basic alternatives do not always suit participants in the selection process. However, they help to understand what exactly is missing in the alternatives under consideration in this situation [1]-[3]. This class of problems is called problems with constructed alternatives. In the modern theory of decision making it is considered that the variants of decisions are character-

ized by different indicators of their attractiveness for DM. These indicators are called features, factors, attributes, or quality measures [2]. They all serve as the criteria for selecting a decision. In the vast majority of real problems, there are many criteria. The complexity of the decision making tasks is also affected by the number of criteria. With a small number of criteria (for example, for two), the task of comparing the two alternatives is fairly simple and transparent, the values of the criteria can be directly compared and a preferred alternative can be developed. With a large number of criteria, the problem becomes immense for the DM. Fortunately, with a large number of criteria, they can usually be combined into groups with a specific semantic meaning. Such groups of criteria are, as a rule, independent. The identification of a structure on a set of criteria makes the decision making process much more meaningful and effective [4]-[10].

The traditional approach to operations research assumes the existence of a single criterion for assessing the quality of the decision [1]. However, the expansion of the field of application of operational research methods led to the fact that analysts began to face problems in which the existence of several criteria for assessing the quality of the solution is essential. The analysis of many real practical problems encountered by the specialists in the investigation of operations naturally led to the appearance of a class of multi-criteria problems. The task of making decisions with several criteria for choosing a decision is the development of the problem of making decisions with a single criterion selection [3], [9], [11].

The Internet of Things (IoT) describes a network of the interconnected smart devices, which are able to communicate with each other for a certain goal. In simple words, the purpose of any IoT device is to connect with other IoT devices and applications (cloud-based mostly) to relay information using data transfer protocols and technologies [12]-[14]. At the same time, the question remains about the choice of the WCT when designing IoT systems. Existing well-known WCTs are rapidly evolving. With an ever-increasing number of available corresponding technologies to choose from, the authors decided it would be helpful to lay out their features and capabilities for easy comparison using multi-criteria decision making [12], [14]-[16].

At the present time, WCTs become increasingly popular alternative in network. Usually a "wireless" network is not built entirely without a cable, but includes wireless devices that communicate with a traditional wired network. Transceivers, referred as "access points" are used for transfer of data between the wireless device or devices, and the wired network [13].

Estimating and choosing the WCT is a rather complicated process for many reasons, including: multi-criteria evaluation in the WCT selection; complexity of preliminary consideration of all possible stages of decision making; taking into account all important criteria when choosing a solution; determination of the priority of the criteria and their weight coefficients and so on [1], [3], [17]-[21].

The purpose of this work is to bring the task of selecting the WCT to a multi-criteria task, taking into account the proposed main criteria, which are major for specialized IoT network and its subsequent solution by one of the multi-criteria decision making methods.

## 2 Related Works and Problem Statement

In recent days, the WCT has become an integral part of several types of communication devices as it allows users to communicate even from remote areas. The devices used for wireless communication are cordless telephones, mobiles, GPS units, ZigBee technology, wireless computer parts, and satellite television, etc. [12], [14], [22]-[23].

In the past years, the wired technologies for the communication were used. These technologies have the greatest drawback of using cable; they are impossible to be used for long distances and also not reliable [12]. To overcome these drawbacks, there was a need to move to the wireless technologies. By using the wireless communication technologies, it is possible to make the communication reliable and cable free. Wireless technologies are used in various applications. For communicating all over the world, wireless communications are connected via satellite [14]. In the closed environments or limited range applications the communication or transferring data occurs with the help of wireless sensor network such as RF modem, Bluetooth, Wi-Fi and Zigbee, etc. The primary advantages of WCT are [22]-[23] reliability and dependability; safety and security; no use of cables; lesser cost than wired one.

An important problem is the choice of the WCT, taking into account the criteria influencing the decision making. The necessity of using the multi-criteria decision making when choosing the WCT in the IoT network is concerned with the complexity of taking into account all features, possibilities and application spheres of WCTs. Besides, an incorrectly selected WCT may lead to the reduction of the reliability and safety of the IoT systems.

Let's consider the most popular WCTs for specialized (home, industrial) IoT network which can be often met in different IoT devices. As a matter of fact, wireless connectivity is not dominated by one single technology [14]. In most cases, the technologies which provide low-power, low-bandwidth communication over short distances, operate on unlicensed spectrum, and have limited quality-of-service (QoS) and security requirements will be widely used for home and indoor environments [15]. Following WCTs (in our case these are alternative decisions) are most suited for this description: Wi-Fi ( $E_1$ ), Z-Wave ( $E_2$ ), Bluetooth ( $E_3$ ), BLE ( $E_4$ ), ZigBee ( $E_5$ ), NFC ( $E_6$ ) and ANT ( $E_7$ ). Each technology has advantages and limitations. The examination of these technologies in detail will be held in order to determine which one is best suited for specialized IoT network [12], [22], [24]-[25].

**Wi-Fi** ( $E_1$ ) is designed for connecting electronic devices in a wireless local area network (WLAN). Wi-Fi is based on the IEEE 802.11 group of standards which operate in the 2.4GHz and 5 GHz unlicensed bands available worldwide. Standards IEEE 802.11b/g/n uses 2.4GHz band, while IEEE 802.11a/n/ac works at 5GHz. Using 14 partially overlapping 22 MHz wide bands in 2.4 GHz frequency, Wi-Fi has a massive bandwidth, and, as a result, allows achieving very fast data rates. The data rate is 54 Mb/s or even more [22]. The main disadvantage of Wi-Fi compared to its competitors is relatively higher power consumption [26]-[27].

**Z-Wave** ( $E_2$ ) is the world market leader in wireless control with over 70 million products sold worldwide, supported by over 450 manufacturers [12]. The main pur-

pose of Z-Wave is to allow reliable transmissions of short messages from a control unit to other nodes in the network [23]. The Z-Wave protocol is an interoperable, wireless communication technology designed for control and monitoring applications for residential and commercial environments [24]. The Z-Wave network allows full mesh topology without the need for a coordinator [28]. The maximum size of the network is restricted to 232 nodes. Physical and media access control layers are defined in ITU-T Recommendation G.9959.

**Bluetooth** ( $E_3$ ) is based on the IEEE 802.15.1 standard for short-range wireless communication between fixed and mobile devices in PANs based on low-cost transceiver microchips in each device [14]. It also works in 2.4 GHz band sharing an overcrowded spectrum with other technologies. The data rate is 3 Mb/s, and 24 Mb/s are supported in v3.0 over a collocated link. A frequency band of Bluetooth is from 2402 MHz to 2480 MHz or from 2400 to 2483.5 MHz with 79 channels, 1 MHz per channel. Bluetooth uses Gaussian frequency-shift keying (GFSK) modulation, but also differential quadrature phase-shift keying ( $\pi/4$ -DQPSK) and differential phase-shift keying (8DPSK) modulations may be used to increase communication data rate [29].

**BLE** ( $E_4$ ) also known as Bluetooth Smart or Bluetooth Low Energy was introduced in Bluetooth v4.0 specification. It is developed for battery-operated devices [22]. It uses 39 channels instead of 79, channel width is 2 MHz instead of 1 MHz, it has lower power consumption and lower data rate, and doesn't provide backward compatibility. Scatternet is also not supported, only point-to-point and star topologies. However, unlike classic Bluetooth, it can support an unlimited number of nodes [24].

**ZigBee** ( $E_5$ ) is a standard for low-power, low-rate wireless communication which aims at interoperability and encompasses devices from different manufacturers. Protocol stack provided by ZigBee is open source and free to use by any developer or company. "Zigbee is the only global, standard-based wireless solution that can conveniently and affordably control the widest range of devices to improve comfort, security, and convenience for consumers" [12]. ZigBee is built upon the physical layer and medium access control layer defined in the IEEE 802.15.4 standard. It uses three unlicensed frequency bands depending on location: from 2400 MHz to 2483.5 MHz, from 902 MHz to 928 MHz, and from 868 MHz to 868.6 MHz [14], [30]-[31].

**NFC** ( $E_6$ ) is a communication technology, which operates in the 13.56 MHz ISM band. At this low frequency, the transmitting and receiving loop antennas function mainly as the primary and secondary windings of a transformer, respectively [30]. Data transfer is via the magnetic field rather than the accompanying electric field because the latter is less dominant at short distances. NFC transfers data at rates up to 424 Kbits/s. As the name suggests, it is designed for very short range communication operating up to a maximum range of 10 cm. This limitation prevents direct competition with Bluetooth low energy, ZigBee, Wi-Fi, and similar technologies [22], [31].

**ANT** ( $E_7$ ) is a proprietary protocol for monitoring and control applications with low power consumption. ANT operates in 2.4 GHz band. It uses virtual channels and works on frequency band from 2400 MHz to 2524 MHz with 124 physical channels with a width of 1 MHz each. ANT packet has 8-byte payload and it is transmitted in 150 microseconds or less [14]. As a result, technology supports data rates of 1 Mb/s.

Every network has a unique identifier to distinguish different network. Multiple virtual channels can coexist on a single frequency. Each ANT node is connected to other nodes through channels [32].

The criteria influence the evaluation and the choice of decisions from the set of alternatives  $E = (E_1, E_2, \dots, E_i, \dots, E_m), i = 1, 2, \dots, m$ , where  $m = 7$  for abovementioned WCT case. The criteria are selected by the developers based on their own experience and depend on the scope of the task. Such tasks are called multi-criteria tasks. The selection of the criteria is an important and rather complex task since it involves the formation of a plurality of factors that influence the decision making. Properly selected criteria allow increasing the efficiency of the decision making while solving multi-criteria problems in various types of their applications.

When selecting the WCT, a large number of the criteria, that is sometimes not relevant and appropriate within the scope of a particular application, is used. According to the various studies and own experience, the authors proposed the use of the following important (main) criteria when selecting WCT for specialized IoT network [24]:

- reliability and dependability of WCT ( $Q_1$ );
- safety and security of data transfer ( $Q_2$ );
- maximum signal range ( $Q_3$ );
- throughput and data rate ( $Q_4$ );
- variety of network topologies ( $Q_5$ );
- applicability of WCT ( $Q_6$ );
- minimum latency ( $Q_7$ );
- wireless power transfer ( $Q_8$ ).

Let's consider in more detail the relevant criteria  $Q_j(E_i)$  and vector criterion

$$Q(E_i) = (Q_1(E_i), Q_2(E_i), \dots, Q_j(E_i), \dots, Q_n(E_i)); E_i \in E; i = 1 \dots 7; j = 1 \dots n,$$

where  $n = 8$  for abovementioned WCT case.

**Reliability and dependability of WCT ( $Q_1$ ).** Reliable packet transfer has a direct influence on battery life and the user experience. Generally, if a data packet is undeliverable due to suboptimal transmission environments, accidental interference from nearby radios, or deliberate frequency jamming, a transmitter will keep trying until the packet is successfully delivered. This comes at the expense of battery life. Moreover, if a wireless system is restricted to a single transmission channel, its reliability will inevitably deteriorate in congested environments [26], [33]-[34].

**Safety and security of data transfer ( $Q_2$ ).** Wireless security is the prevention of unauthorized access or damage to IoT devices using wireless network. The most common types of wireless security are Wired Equivalent Privacy (WEP) and Wi-Fi Protected Access (WPA). WPA was a quick alternative to improve security over WEP. The current standard is WPA2. Some hardware cannot support WPA2 without firmware upgrade or replacement. WPA2 uses an encryption device that encrypts the network with a 256-bit key. The longer key length improves security over WEP. En-

terprises often enforce security using a certificate-based system to authenticate the connecting device, following the standard 802.1X [22]-[25], [35].

**Maximum signal range ( $Q_3$ ).** The range of a wireless technology is often thought of as being proportional to the power output of the transmitter combined with the RF sensitivity of a receiver measured in decibels (the “link budget”). Higher power transmission and greater sensitivity increase range because of the effective improvement in the signal to noise ratio (SNR). SNR is a measure of the ability of a receiver to correctly extract and decode a signal from the ambient noise. At a threshold SNR, the BER exceeds the radio’s specification and communication fails. A Bluetooth low energy receiver, for example, is designed to tolerate a maximum BER of only around 0.1%. Maximum power output in the license free 2.4 GHz ISM band is limited by regulatory bodies [14], [23].

**Throughput and data rate ( $Q_4$ ).** Transmissions by low-power wireless technologies comprise two parts: the bits implementing the protocol (for example, packet ID and length, channel, and checksum, collectively known as the “overhead”) and the information that’s being communicated (known as the “payload”). The ratio of payload/overhead + payload determines the protocol efficiency. Low-power wireless technologies generally require the periodic transfer of small amounts of sensor information between sensor nodes and a central device, while minimizing power consumption, so bandwidths are typically modest [12], [14], [25].

**Variety of network topologies ( $Q_5$ ).** Literature analysis show that WCTs support up to five main network topologies [6]-[8], [22]. *Broadcast*: a message is sent from a transmitter to any receiver within range. The channel is unidirectional with no acknowledgement that the message has been received. *Peer-to-peer*: two transceivers are linked on a bi-directional channel whereby messages can be acknowledged and data can be transferred both ways. *Star*: a central transceiver communicates across bi-directional channels with several peripheral transceivers. The peripheral transceivers can’t directly communicate with each other. *Scanning*: a central scanning device remains in receive mode, waiting to pick up a signal from any transmitting device within range. Communication is in one direction [30].

**Applicability of WCT ( $Q_6$ ).** This criterion shows the level of applicability of the WCT. Consider some areas of application: home-security systems, sensor-based lighting, smart streetlights, wearable application (fitness, medical), sensor network, indoor navigation, industrial automation, home metering, smart-home applications, smart city, etc. [23], [32], [36]-[37].

**Minimum latency ( $Q_7$ ).** The latency of a wireless system can be defined as the time between a signal being transmitted and received. While typically only a matter of milliseconds, it is an important consideration for wireless applications. The following list compares latencies for some WCTs (note that once again that these are dependent on configuration and operating conditions): ANT – negligible, Wi-Fi – 1.5 milliseconds (ms), BLE – 2.5 ms, ZigBee – 20 ms, NFC – polled typically every second (but can be specified by the product manufacturer) [23].

**Wireless power transfer ( $Q_8$ ).** is a generic term for a number of different technologies for transmitting energy by means of electromagnetic fields. The existing

WCTs differ in the distance over which they can transfer power efficiently, whether the transmitter must be aimed (directed) at the receiver, and in the type of electromagnetic energy they use: time varying electric fields, magnetic fields, radio waves, microwaves, infrared or visible light waves. Wireless power uses the same fields and waves as wireless communication devices like radio, another familiar technology that involves electrical energy transmitted without wires by electromagnetic fields, used in cellphones, radio and television broadcasting, and WiFi [12], [14], [24].

The multi-criteria problem can be formulated on the basis of the developed criteria and set of alternative decisions, and can be solved using one of the appropriate methods of MCDM, in particular, the ideal point method [1], [3].

### 3 Multi-Criteria Problem Statement for WCT selection

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 found through the use of such methods as the selection of the main criterion, the linear, multiplicative and max-min convolutions, the ideal point method, the sequential concessions methodology, the lexicographic optimization [1], [3], [8]-[9], [38]-[39].

Most of the methods of multi-criteria decision making provide transformation of a multi-criteria problem into the one-criterion, which greatly simplifies the decision making process [1], [3].

In most cases, the choice of the WCT comes to the comparative analysis of their capabilities and taking into account the pricing policy for deployment and support of the corresponding technologies for their own IoT devices in specialized IoT network. Besides, IoT developers often give preference to the well-known WCTs, without considering the criteria that in the future may affect the development, maintenance, updating, reliability, safety and scaling of the developed IoT systems [30], [40]-[41].

At the present time, there are several known methods of expert evaluation and selection of WCT, in particular, the analytic hierarchy process, the paired-comparison method, the Delphi method, fuzzy technologies and methods [2], [9], [42]-[48]. At that, the considered methods and approaches have some limitations and peculiarities of application, in particular, the necessity of calculation of the consistency of expert judgments; the limited number of levels of the hierarchy and the dimension of the paired-comparison matrix; the constant contact with experts for conducting the questionnaires; the need to update the structure of the model when changing the number of criteria and alternatives, etc. [2]-[3], [49]-[52].

The task of selecting the WCT is bring to a multi-criteria decision-making problem and has the following form (decisions matrix):

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

where  $Q(E_i)$  is a vector criterion of quality for  $i$ -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 by the  $j$ -th criterion  $Q_j(E_i)$  have a certain scale of assessment and is presented by experts based on their experience, knowledge and experimental research in the field of WCT for specialized IoT network [3].

To solve the WCT selection problem, it is necessary to find the best alternative  $E^* \in E$  using data (1):

$$E^* = \underset{i=1..m}{\text{Arg Max}}(Q(E_i)), E_i \in E, i = 1..7.$$

#### 4 Ideal Decision for Solving Multi-Criteria Decision Problem

To solve the problem of multi-criteria selection of the WCT for specialized IoT network there is a sufficient number of well-known multi-criteria decision making methods. Such as lexicographic optimization method, suboptimization method, linear convolution method, multiplicative convolution method, max-min convolution method, method of taking into account acceptable limits of criteria, ideal point method, etc. For some of them, it is necessary to determine the weight coefficients of the criteria, which sometimes is difficult with a large number of criteria [1], [3], [9], [49].

Let's apply one of the existing multi-criteria decision making methods, for example, ideal point method to solve the corresponding task of multi-criteria selection of the WCT for specialized IoT network [1].

The *ideal point method* implements the principle of an ideal decision. It postulates the existence of an "ideal point" for solving a problem in which the extremum of all criteria is achieved. Since the ideal point in most cases is not among the existing solutions, then there is a problem finding the "nearest" to the ideal permissible point. It would have been nice if there was a single objective notion of "distance", but it was not. If on a Cartesian two-dimensional subspace it is possible to apply the Euclidean metric, then, for example, the shortest path on the surface of a sphere is an arc, and not a straight line [1], [3], [49].

Thus, for solving the multi-criteria task using the ideal point method, it is necessary above all:

- determine the coordinates of the ideal point;
- select a metric which you can measure the distance to the ideal point.

To determine the coordinates of the ideal point you need to solve  $n$  one-criterion tasks for each of the optimization criteria:

$$Q_j(E_i) \Rightarrow \text{Max}; E_i \in E; (i = 1, 2, \dots, m; j = 1, 2, \dots, n). \quad (2)$$

Optimal values of the criteria for each of the one-criterion problems

$$Q_j^* \Rightarrow \underset{i \in \{1, 2, \dots, m\}}{\text{Max}} Q_j(E_i); E_i \in E; (i = 1, 2, \dots, m; j = 1, 2, \dots, n), \quad (3)$$



where  $Q_j^*$  is the optimal value of the  $j$ -th criterion;  
will be the coordinates of the ideal point in the criteria space

$$Q^* = (Q_1^*, Q_2^*, \dots, Q_n^*), \quad (4)$$

where  $Q^*$  is the ideal point;  $Q_1^*, Q_2^*, \dots, Q_n^*$  are optimal values of  $n$  criteria (coordinates of the ideal point).

If the ideal point  $Q^*$  is permissible (but this happens very rarely), then the decision  $E^*$  is considered to be obtained. Otherwise, it is necessary to determine the distance  $d_\rho(E_i), (i = 1, 2, \dots, m)$  to the ideal point  $Q^*$ . To do this, it is necessary to choose a metric and finally to solve a one-criterion task of finding a point from the set of admissible decisions, which is closest to the ideal one [1].

Thus, the optimization problem takes the following form:

$$d_\rho(E_i) = \rho(Q(E_i) - Q^*) \Rightarrow \text{Min}; E_i \in E; (i = 1, 2, \dots, m), \quad (5)$$

where  $d_\rho(E_i)$  is a distance from ideal point  $Q^*$  to  $i$ -th alternative  $Q(E_i)$ ;  $\rho$  is a metric for measure the distance to the ideal point  $Q^*$ .

If the Euclidean metric [1] is chosen, then the criterion (5) takes the form:

$$d_\rho(E_i) = \sqrt{\sum_{j=1}^n (Q_j(E_i) - Q_j^*)^2} \Rightarrow \text{Min}; E_i \in E; (i = 1, 2, \dots, m; j = 1, 2, \dots, n), \quad (6)$$

where  $Q_j(E_i)$  are the coordinates of the  $i$ -th alternative in the criteria space;  $Q_j^*$  are the coordinates of the ideal point.

If the Hamming metric [3] is chosen, then the criterion (5) takes the form:

$$d_\rho(E_i) = \sum_{j=1}^n |Q_j(E_i) - Q_j^*| \Rightarrow \text{Min}; E_i \in E; (i = 1, 2, \dots, m). \quad (7)$$

Let us apply the ideal point method for multi-criteria selection of the WCT for specialized IoT network

$$E^* = \text{Arg Max}_{i=1 \dots m} (Q_\rho(E_i)), E_i \in E, i = 1 \dots 7.$$

## 5 Example of Multi-Criteria Selection of the WCT Using Ideal Point Method

Experts are invited to evaluate alternative decisions (WCTs)  $E_1, E_2, \dots, E_7$  according to the specified criteria  $Q_1, Q_2, \dots, Q_8$  using the 10-point rating scale (from 0 to 9),

where 9 points corresponds to the largest (the best) value of the alternative decision by the criterion.

Let us consider an example with experts' evaluation of the specified criteria  $Q_j(E_i)$  for WCT selection in the case of experts' data, presented in Table 1.

It is necessary to form a Pareto-optimal set  $E$  of effective alternatives by consistently excluding dominated alternatives from initial set. If there is an alternative over which the current dominates, then it is excluded from further consideration. If some alternative is dominant over the current one, then remove the last one from the consideration and go to the alternate, following the current one and not excluded from the consideration. The process continues until the current alternative is not to compare. The alternatives that remain will be Pareto-optimal [1], [3]. In our case (Table 1), all alternatives remain and are Pareto-optimal.

Let us find the coordinates of the ideal point (2) as the maximum values (3) of all the criteria.

The maximum value of the criterion  $Q_1^*$  corresponds to the sixth alternative  $E_6$  :

$$\text{Max}_{i \in \{1, 2, \dots, m\}} Q_1(E_i) = Q_1(E_6) = 9; E_i \in E; (i = 1, 2, \dots, 7).$$

**Table 1.** Decisions matrix for multi-criteria selection of the WCT

	$E_1$	$E_2$	$E_3$	$E_4$	$E_5$	$E_6$	$E_7$
$Q_1$	6	8	7	8	8	9	8
$Q_2$	8	7	6	7	7	9	9
$Q_3$	8	5	7	6	7	3	4
$Q_4$	7	7	9	9	6	5	8
$Q_5$	5	7	6	6	7	5	8
$Q_6$	9	8	9	9	8	6	6
$Q_7$	6	3	5	4	3	7	8
$Q_8$	7	5	6	6	5	3	4

The maximum value of the criterion  $Q_2^*$  corresponds to the sixth  $E_6$  and the seventh  $E_7$  alternatives:

$$\text{Max}_{i \in \{1, 2, \dots, m\}} Q_2(E_i) = Q_2(E_6, E_7) = 9; E_i \in E; (i = 1, 2, \dots, 7).$$

The maximum value of the criterion  $Q_3^*$  corresponds to the first  $E_1$  alternative:

$$\text{Max}_{i \in \{1, 2, \dots, m\}} Q_3(E_i) = Q_3(E_1) = 8; E_i \in E; (i = 1, 2, \dots, 7).$$

The maximum value of the criterion  $Q_4^*$  corresponds to the third  $E_3$  and the fourth  $E_4$  alternatives:

$$\text{Max}_{i \in \{1, 2, \dots, m\}} Q_4(E_i) = Q_4(E_3, E_4) = 9; E_i \in E; (i = 1, 2, \dots, 7).$$

The maximum value of the criterion  $Q_5^*$  corresponds to the seventh  $E_7$  alternative:

$$\text{Max}_{i \in \{1, 2, \dots, m\}} Q_5(E_i) = Q_5(E_7) = 8; E_i \in E; (i = 1, 2, \dots, 7).$$

The maximum value of the criterion  $Q_6^*$  corresponds to the first  $E_1$ , the third  $E_3$  and the fourth  $E_4$  alternatives:

$$\text{Max}_{i \in \{1, 2, \dots, m\}} Q_6(E_i) = Q_6(E_1, E_3, E_4) = 9; E_i \in E; (i = 1, 2, \dots, 7).$$

The maximum value of the criterion  $Q_7^*$  corresponds to the seventh  $E_7$  alternative:

$$\text{Max}_{i \in \{1, 2, \dots, m\}} Q_7(E_i) = Q_7(E_7) = 8; E_i \in E; (i = 1, 2, \dots, 7).$$

The maximum value of the criterion  $Q_8^*$  corresponds to the first  $E_1$  alternative:

$$\text{Max}_{i \in \{1, 2, \dots, m\}} Q_8(E_i) = Q_8(E_1) = 7; E_i \in E; (i = 1, 2, \dots, 7).$$

Consequently, the ideal point  $Q^*$  (4) in the criteria space  $\{Q_1, Q_2, \dots, Q_8\}$  has following coordinates:

$$Q^* = (Q_1^*, Q_2^*, Q_3^*, Q_4^*, Q_5^*, Q_6^*, Q_7^*, Q_8^*) = (9, 9, 8, 9, 8, 9, 8, 7).$$

The ideal point  $Q^*$  is not equivalent to any of the alternative decision  $E_1, E_2, \dots, E_7$ , so find the distances between such alternatives and the ideal point (5) using the Euclidean metric (6). An alternative that has the smallest distance  $Q_\rho(E_i)$  will be the optimal by the ideal point method.

The distance (6), for example, from the criteria vector  $Q_\rho(E_3)$  to ideal vector  $Q^*$  is:

$$d_\rho(E_3) = \sqrt{(7-9)^2 + (6-9)^2 + \dots + (6-7)^2} = 5.292$$

and at the same time, this distance (5) can be calculated using Hamming metric (7)

$$d_\rho(E_3) = |7-9| + |6-9| + \dots + |6-7| = 12.$$

The distances between vectors  $d_\rho(E_i)$  for all alternatives  $E_1, E_2, \dots, E_7$  and ideal vector  $Q^*$  are given in Table 2 based on Euclidean and Hamming metrics.

**Table 2.** Comparison of the distances between vectors  $Q_\rho(E_i)$  for all alternatives and ideal vector  $Q^*$  based on Euclidean and Hamming metrics

	$E_1$	$E_2$	$E_3$	$E_4$	$E_5$	$E_6$	$E_7$
Euclidean metric	5.196	7.0	5.292	5.477	6.782	8.718	6.0
Hamming metric	11.0	17.0	12.0	12.0	16.0	20.0	12.0

According to (5), (6), the minimal distance is

$$\underset{i \in \{1, 2, \dots, 7\}}{\text{Min}} d_\rho(E_i) = d_\rho(E_1) = 5.196$$

and the ranking row of decisions (Table 2) can be presented in such way

$$E_1 \succ E_3 \succ E_4 \succ E_7 \succ E_5 \succ E_2 \succ E_6. \quad (8)$$

Thus, the first alternative  $E_1$  (Wi-Fi WCT) is optimal decision according to the ideal point method with implementation of the Euclidean metric for data (Table 1).

According to Hamming metric (7) for the data (Table 2), the minimal distance is

$$\underset{i \in \{1, 2, \dots, 7\}}{\text{Min}} d_\rho(E_i) = d_\rho(E_1) = 11$$

and ranking row (8) has some changes

$$E_1 \succ (E_3 = E_4 = E_7) \succ E_5 \succ E_2 \succ E_6. \quad (9)$$

It means, that for evaluation data (Table 1), the "Wi-Fi" is the most rational WCT for specialized IoT network (according to both metrics (5),(7)).

The results (8), (9) of using the ideal point method with two proposed metrics (Euclidean and Hamming metrics) give the best decision  $E_1$  (Table 2), which also coincides with the results of the expert survey. But the use of the Euclidean metric (6) gives a more accurate results (8) of distances between alternatives and ideal point. This makes it possible to clearly identify the advantage of one criterion over another in the process of their ranking. The application of the Hamming metric (7) does not give a clear advantage of one criterion over another, indicating the equality (9) of the three criteria  $E_3, E_4, E_7$ . The choice of metrics remains by experts and DM.

The considered approach to solving multi-criteria problems can be easily integrated into various tasks, in particular, for solving vehicle routing problems [53], choosing a transport company [54], for evaluating renewable power generation sources [50], for location selection for modern agri-warehouses [51], assessing the cooperation level within the consortium "University - IT Company" [7] and others. For solving various planning and optimization tasks in uncertainty it is possible to use special

methods, models and algorithms for decision-making processes, which take in to account different kind of uncertainties [55]-[56].

## 6 Conclusions

The necessity of using the multi-criteria decision making for selection of the WCT for specialized IoT network is concerned with the complexity of the selection process is due to the large number of existing WCTs, which are available on the IoT communications market, and the variety of their features, possibilities and spheres of applications. Besides, an incorrectly selected WCT may lead to the reduction of the reliability and safety of the IoT systems.

For solving multi-criteria decision making problem, authors use the ideal point method with different metrics (Euclidean and Hamming metrics) to calculate the distance between alternatives (Table 2). Special attention is paid to the impact analysis of various metrics on the results of the WCT selection. The reliability, dependability, safety and security of IoT systems are considered as the most important criteria for decision making in WCT selection processes.

A detailed analysis of the features and capabilities of the WCT using the mathematical apparatus of multi-criteria decision making allows determining the best solution and the further analysis of the results more accurately.

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