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Strategic Management of Wireless Communication Challenges: Data-Driven Analysis for Enhanced Efficiency and Scalability in Uncertain Environment

Aditi Biswas[1], Kamal Hossain Gazi[2], Arijit Ghosh[3], Sankar Prasad Mondal[2*]

[1] Department of Basic Science and Humanities, Greater Kolkata College of Engineering and Management, 743387 Kolkata, India
[2] Department of Applied Mathematics, Maulana Abul Kalam Azad University of Technology, West Bengal, 741249 Nadia, West Bengal, India
[3] Department of Mathematics, St. Xavier's College (Autonomous), 700016 Kolkata, India

[*] Correspondence: Sankar Prasad Mondal (sankar.mondal02@gmail.com)

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Abstract: Wireless communication technology has transformed connectivity across industries, but its widespread adoption comes with significant challenges. The purpose of paper is to identify and analyze the most critical obstacles affecting the efficiency, reliability, and scalability of wireless communication systems. This research paper mainly demonstrates to determine the most effective challenges for wireless communication technology. In recent times, it is really very significant and demanding work of this technology-based society. Interference, security vulnerabilities, bandwidth limitations, signal attenuation, and latency concerns etc. are the basic factors of this challenging work. This study explores the application of multi-criteria decision making (MCDM) techniques using intuitionistic fuzzy numbers (IFNs) to evaluate this. We apply the weighted MCDM method, i.e., Entropy in this paper. The decisions of multiple decision makers (DMs) are considered into account when collecting this problem related data and IFNs are utilised as mathematical tools to handle uncertainty. In order to address the ambiguity and inconsistency of the system, we finally conclude to conduct the analysis here with final result.

Keywords: Wireless communication technology; Discrete intuitionistic fuzzy numbers; MCDM methodology; Entropy

1 Introduction

Wireless communication technology has adapted modern connectivity, with vast data exchange across diverse applications, from mobile phones to Internet of Things (IoT) devices [1, 2]. It encounters various complex challenges that effect its efficiency, reliability and scalability. The main causes include the particular spectrum availability, weaknesses in security and signal interference in the transmission of valuable data. Different technological challenges [1, 3, 4] arise from the growing demand for faster data rates and connectivity of low-latency, particularly as 5G and beyond are introduced. For battery-powered devices and large-scale deployments, energy efficiency is a big concern. Various environmental factors, i.e., weather and topography, have an additional effect on signal propagation. Identifying these challenges and getting the noble solutions in hardware design, network protocols and regulatory frameworks. Wireless communication [5] can better support upcoming developments in connectivity and digital transformation to overcome these barriers.

To select the ideal option, multi-criteria decision making (MCDM) methods consider multiple criteria. In the enormous field of operations research, it has various procedures for discovering the criteria weight. Several well-known MCDM processes, such as, Analytic Hierarchy Process (AHP) [6], Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [7], Criteria Importance Through Intercriteria Correlation (CRITIC) [7], Complex Proportional Assessment (COPRAS) [8], Multi-Objective Optimization based on Ratio Analysis plus Full Multiplicative form (MULTIMOORA) [9], VIekriterijumsko KOmpromisno Rangiranje (VIKOR) [10], Elimination and Choice Translating Reality (ELECTRE) [11], Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) [12] etc. are applied to identify the actual decision-making issues. The above explained decision making processes help to make the perfect and wise decision for adoptation of wireless communication technology.

The main motive of this paper is to figure out the most effective and difficult challenges for wireless communication technology. The motivation for this paper are described here. The multiple criteria are considered to determine the most effective challenges for wireless communication technology. Intuitionistic Fuzzy Numbers (IFNs) are taken for capturing the uncertainty of the data set. All the data are taken in linguistic terms and converted into IFNs. The new score and accuracy functions are developed and applied this new score function to process the fuzzy value. Calculate the criteria weight of each criterion using the decision matrix and utilise it in further evaluation. If DIFN based MCDM model is constructed, namely fuzzy Entropy and it determine the criteria weight. Two decision makers (DMs) are given data in linguistic terms in an unbiased process.

We determine the most effective challenges for adaptation of wireless communication technology, which is the main purpose of this paper. Seven critical criteria are considered for this easy analysis. An MCDM process is selected as optimization tools and Discrete Intuitionistic Fuzzy Numbers (DIFNs) are appraised as uncertain tools. Data are gathered in an unbiased process and numerically evaluated the result on it.

The structure of this research work is discussed in detail in this section. Section 1 describes the introduction, motivation and research outline of this work. A brief literature review on the total work shown in Section 2. The basic fuzzy set concept and intuitionistic fuzzy set idea is described in Section 3. A MCDM technique, namely Entropy weighted method that is used in this study, is demonstrated in Section 4. The criteria selection and alternatives to determine the most effective challenges for wireless communication technology are fully discussed in Section 5 and Section 6, respectively. Application of decision making framework of this research is mentioned in Section 7. Additionally, the sensitivity analysis of this study is presented in Section 8. Finally, the conclusion, research implication and future research scope are presented in Section 9.

2 Literature Survey of this Study

This section explains the literature survey of this study. Literature studies on wireless communication technology, Intuitionistic Fuzzy Number (IFN) and Entropy methodology, respectively, are described below in detail.

2.1 Background on Wireless Communication Technology

Wireless communication technology [13] is a popular technology nowadays and it allows for immediate communication with mobile phones and the internet, creating the seamless connectivity. It enables data transfer without any help of physical connections, using radio waves or many other electromagnetic signals. It boosts emergency response with GPS tracking. It also confirms remote work and online education and powers smart homes. Through telemedicine and remote monitoring, healthcare benefits from wireless technology, while industries apply it for automation and real-time data exchange. Further, it enhances pleasure via streaming and social media.

Prakash et al. [1] explained the comprehensive review of IoT, wireless communication, sensors and hardware for agricultural automation. Aman et al. [3] explained the security system of underwater and air–water wireless communication. Li and Wang [14] expressed edge computing with artificial intelligence for evaluation of the teaching quality. For advanced underground mining operations, Theissen et al. [15] evaluated the wireless communication technologies. Chandan et al. [16] discussed secure modern wireless communication network according to blockchain technology. It powers several applications, i.e., mobile networks [2], Wi-Fi [17], Bluetooth [18] and IoT devices [1], etc. This technology gives the flexibility and connectivity to many industries. In 2019, Islam and Jin [19] talked about the wireless communication network and Yan [20] is also explained this in 2024. Moreover, in 2017 and 2012, Sengaliappan and Kumaravel [13] and Gupta [21] also evaluatedon it respectively in the research paper, respectively.

2.2 Background of Intuitionistic Fuzzy Number (IFN)

Fuzzy set has the ability to catch the uncertainty and vagueness of the data set and model. It's applied in optimization, differential equations [22] and difference equations [23] in various studies.

Here, we apply the Intuitionistic Fuzzy Number (IFN) to obtain an accurate presentation of this research work in the uncertain environment throughout the MCDM process. Even in an ambiguity environment, it is feasible to effectively convey uncertainty by exhibiting decision-making ability in various contexts and for various reasons. There are many several applications where Intuitionistic Fuzzy Number (IFN) are used, s.t., evaluation of various states in India on women empowerment [24], use of the airport performance from the passengers' perspective [25], application in Neural network [26], application in manufacturing and inspection during energy production using sustainable life cycle in industry 4.0 [27] and many more.

2.3 Literature of Entropy Method

MCDM [28] is a popular decision making technique for various real world problems. And, the Entropy-based decision making method measures the uncertainty in the data in order to identify the relative significance of criteria in decision-making. It allocates the criteria weights on the variability of information, where higher variation demonstrates the big importance. To choose the best alternatives, it is frequently used in several domains including engineering, business and environmental management, etc.

Now, we have discussed in detail the various applications of the entropy method. It is applied in numerous fields including the medical field [29], site selection [30], financial optimization [31], supply chain [32] and so on. To evaluate the criteria weights, the MCDM process, i.e., Entropy method, is used to process the problem. Shannon [33] invented this methodology in 1948. This approach is adaptable and flexible, that can be applied in different complex decision-making situations. The Entropy procedure has been used in several research works of various areas in real life problems. This MCDM method is used in plenty of areas, including select the materials in the engineering sector [34], a suitable site selection for a hospital [35], computing enduring women's empowerment [24] and so on. Moreover, the Entropy methodology was applied to use the fuzzy Entropy measure [36] to the generalised distance measure.

3 Preliminaries of Mathematical Tools

We can find the initial base of fuzzy sets, fuzzy numbers and their spread, like intuitionistic fuzzy sets, in this section. Fuzzy set is a mathematical concept from the illustration of classical set theory and intuitionistic fuzzy set is the extension of fuzzy set theory. Here, we discuss both of them with their properties, numerical example and a new de-fuzzification method.

3.1 Fuzzy Set and Fuzzy Number

In 1965, fuzzy sets were first introduced by Zadeh [37] to handle the uncertain circumstances. The proper definition and initial properties of it are explained as below:

Definition 1. Fuzzy Set: [37]

Let us choose, p be an arbitrary element of $\tilde{\mathscr{F}}$ where $\mathscr{U}$ be a universal set. Therefore, the fuzzy set $\tilde{\mathscr{F}}$ on $\mathscr{U}$ is denoted as follows,

$$\tilde{\mathscr{F}} = \{(p, \mu_{\tilde{\mathscr{F}}}) : p \in \mathscr{U}\} \tag{1}$$

where, the membership value is $\mu_{\tilde{\mathscr{F}}}(p) : \mathscr{U} \to [0,1]$ of the element p in $\tilde{\mathscr{F}}$.

Definition 2. Fuzzy Number: [38]

A fuzzy set $\mathscr{F}$ on the set of real numbers $\mathbb{R}$ maintain the following contexts, these are,

(i) $\tilde{\mathscr{F}}$ need to be the normal fuzzy set, s.t., $\exists$ an element $q \in \tilde{\mathscr{F}}$ i.e., $\mu_{\tilde{\mathscr{F}}}(q) = 1$.

(ii) ${}^{\alpha}\tilde{\mathscr{F}}$ must be a closed interval for every $\alpha \in (0,1]$, which is defined that, ${}^{\alpha}\tilde{\mathscr{F}} = \left\{q : \mu_{\tilde{\mathscr{F}}}(q) \geq \alpha\right\}$ is closed.

(iii) ${}^{\alpha}\tilde{\mathscr{F}}$ need to be a convex fuzzy set.

(iv) The support of $\tilde{\mathscr{F}}$ must be bounded, s.t., Support $\tilde{\mathscr{F}} = {}^{0}\tilde{\mathscr{F}} = \{q : \mu_{\mathscr{F}}(q) \geq 0\}$ is bounded.

(v) The membership function of $\tilde{\mathscr{F}}$ need to be the piecewise continuous.

3.2 Intuitionistic Fuzzy Numbers (IFN)

Intuitionistic Fuzzy Numbers (IFN) was first introduced by Atanossov and Gargov [39] in 1989. For presenting an unknown quantity, the intuitionistic fuzzy numbers [25] play an important role. Like fuzzy numbers, IFN has a concept of membership function associated with another characteristic function, namely the non-membership function. Fuzzy set has various extensions, like intuitionistic fuzzy set [26], neutrosophic set [40], interval fuzzy set [39], type-2 set [41] and so on. The IFN is a triplet ordered pair where the first is the element itself followed by membership and non-membership functions.

Definition 3. Intuitionistic Fuzzy Set (IFS): [25]

Choose that, $\mathscr{U}$ be a universal set and an Intuitionistic Fuzzy Set (IFS) denoted by $\tilde{\mathscr{H}}$ and explain as,

$$\tilde{\mathscr{H}} = \left\{\left(r, \mu_{\mathscr{H}}(r), \nu_{\tilde{\mathscr{H}}}(r)\right) : r \in \mathscr{U}\right\} \tag{2}$$

where, $\mu_{\mathscr{H}}(r) : \mathscr{U} \to [0,1]$ and $\nu_{\mathscr{H}}(r) : \mathscr{U} \to [0,1]$ are the membership and non-membership function, respectively, with $0 \leq \mu_{\mathscr{H}}(r) + \nu_{\mathscr{H}}(r) \leq 1$ for any $r \in \mathscr{U}$.

Definition 4. Intuitionistic Fuzzy Number (IFN): [24]

An Intuitionistic Fuzzy Number (IFN) is an Intuitionistic Fuzzy Set (IFS) that defines on ($\mathbb{R}$), the set of real numbers and must satisfy the properties of fuzzy numbers (Definition 2). So, the IFN can be represented as,

$$\tilde{\mathscr{H}} = \left\{\left(r, \mu_{\tilde{\mathscr{H}}}(r), \nu_{\tilde{\mathscr{H}}}(r)\right) : r \in \mathbb{R}\right\} \tag{3}$$

where, $\mu_{\tilde{\mathscr{H}}}(r) : \mathbb{R} \rightarrow [0,1]$ and $\nu_{\tilde{\mathscr{H}}}(r) : \mathbb{R} \rightarrow [0,1]$ are the membership and non-membership function, respectively, with $0 \leq \mu_{\tilde{\mathscr{H}}}(r) + \nu_{\tilde{\mathscr{H}}}(r) \leq 1$ for any $r \in \mathbb{R}$.

Definition 5. Discrete Intuitionistic Fuzzy Number (DIFN):

An Discrete Intuitionistic Fuzzy Number (DIFN) is defined on the set of real numbers ($\mathbb{R}$) and must maintain the properties of fuzzy numbers (Definition 2). So, the DIFN is represented as,

$$\tilde{\mathscr{H}} = \left\{ \left(r, \mu_{\tilde{\mathscr{H}}}(r), \nu_{\tilde{\mathscr{H}}}(r) \right) : r \in \mathbb{R} \right\} \tag{4}$$

where, $r, \mu_{\tilde{\mathscr{H}}}(r)$ and $\nu_{\tilde{\mathscr{H}}}(r)$ are distinct number, Here, $\mu_{\tilde{\mathscr{H}}}(r) : \mathbb{R} \rightarrow [0,1]$ and $\nu_{\tilde{\mathscr{H}}}(r) : \mathbb{R} \rightarrow [0,1]$ are the membership and non-membership function, respectively, and $0 \leq \mu_{\mathscr{H}}(r) + \nu_{\mathscr{H}}(r) \leq 1$ for any $r \in \mathbb{R}$.

3.3 Arithmetic Operations of Discrete Intuitionistic Fuzzy Number (DIFN)

This section mainly expresses the arithmetic operations of DIFNs. Some basic arithmetic operations, such as addition, scalar multiplication, multiplication and scalar power on DIFNs are described here.

In this paper, we consider that, $\tilde{\mathscr{H}} = \{(r, \mu_{\mathscr{H}}(r), \nu_{\mathscr{H}}(r)) : r \in \mathbb{R}\}$ and $\tilde{\mathscr{J}} = \left\{ \left(s, \mu_{\tilde{\mathscr{J}}}(s), \nu_{\tilde{\mathscr{J}}}(s) \right) : s \in \mathbb{R} \right\}$ are two DIFNs define on $\mathbb{R}$. Then, $\exists$ some arithmetic operations, they are,

(i) Addition of two DIFNs:

The addition of the above described two DIFNs $\tilde{\mathscr{H}}$ and $\tilde{\mathscr{J}}$ is define as,

$$\begin{aligned} \tilde{\mathscr{H}} \oplus \tilde{\mathscr{J}} &= \left\{ \left\langle (r+s); \mu_{\tilde{\mathcal{H}} \oplus \tilde{\mathcal{J}}}, \nu_{\tilde{\mathcal{H}} \oplus \tilde{\mathcal{J}}} \right\rangle \right\} \\ &= \left\{ \left\langle (r+s); \mu_{\tilde{\mathcal{H}}} + \mu_{\tilde{\mathcal{J}}} - \mu_{\tilde{\mathcal{H}}}\mu_{\tilde{\mathcal{J}}}, \nu_{\tilde{\mathcal{H}}}\nu_{\tilde{\mathcal{J}}} \right\rangle \right\} \end{aligned} \tag{5}$$

(ii) Scalar Multiplication of DIFNs:

If δ is the positive real number ($\delta \in \mathbb{R}^{+}$). Then, the scalar multiplication (δ) of DIFN $\tilde{\mathscr{H}}$ is,

$$\begin{aligned} \delta\tilde{\mathscr{H}} = \delta \times \tilde{\mathscr{H}} &= \left\{ \left\langle \delta r; \mu_{\delta\tilde{\mathscr{H}}}, \nu_{\delta\tilde{\mathscr{H}}} \right\rangle \right\} \\ &= \left\{ \left\langle \delta r; 1 - \left(1 - \mu_{\tilde{\mathscr{H}}}\right)^{\delta}, \left(\nu_{\tilde{\mathscr{H}}}\right)^{\delta} \right\rangle \right\} \end{aligned} \tag{6}$$

(iii) Multiplication of two DIFNs:

The multiplication of two DIFNs $\tilde{\mathscr{H}}$ and $\tilde{\mathscr{J}}$ is denote as,

$$\begin{aligned} \tilde{\mathscr{H}} \otimes \tilde{\mathscr{J}} &= \left\{ \left\langle rs; \mu_{\tilde{\mathscr{H}} \otimes \tilde{\mathscr{J}}}, \nu_{\tilde{\mathscr{H}} \otimes \tilde{\mathscr{J}}} \right\rangle \right\} \\ &= \left\{ \left\langle rs; \mu_{\tilde{\mathscr{H}}}\mu_{\tilde{\mathscr{J}}}, \nu_{\tilde{\mathscr{H}}} + \nu_{\tilde{\mathscr{J}}} - \nu_{\tilde{\mathscr{H}}}\nu_{\tilde{\mathscr{J}}} \right\rangle \right\} \end{aligned} \tag{7}$$

(iv) Power of DIFN:

Consider λ be a natural number ($\lambda \in \mathbb{N}$). Then the scalar power (λ) of DIFN $\tilde{\mathscr{H}}$ is,

$$\begin{aligned} \tilde{\mathscr{H}}^{\lambda} &= \left\{ \left\langle r^{\lambda}; \mu_{\tilde{\mathscr{H}}^{\lambda}}, \nu_{\tilde{\mathscr{H}}^{\lambda}} \right\rangle \right\} \\ &= \left\{ \left\langle r^{\lambda}; \left(\mu_{\tilde{\mathscr{H}}}\right)^{\lambda}, 1 - \left(1 - \nu_{\tilde{\mathscr{H}}}\right)^{\lambda} \right\rangle \right\} \end{aligned} \tag{8}$$

3.4 Score and Accuracy Functions of DIFN

This section describes the score function and accuracy function of Discrete Intuitionistic Fuzzy Number (DIFN). Since there is no order relation on the DIFNs, then two numbers can't be comparable. The score and accuracy functions on DIFN provide a crisp value corresponding to DIFN which can be comparable by the usual Euclidean metric space. There are various score and accuracy functions [35] defined in different fuzzy numbers. Here, proposed score and accuracy functions on DIFNs are as follows:

Definition 6. Score functions of DIFN:

Consider, from a Discrete Intuitionistic Fuzzy set $\tilde{\mathscr{H}} = \{(r, \mu_{\mathscr{H}}(r), \nu_{\mathscr{H}}(r)) : r \in \mathbb{R}\}$, we can represent the DIFN $\tilde{\mathscr{H}} = \langle \mu_{\tilde{\mathscr{H}}}, \nu_{\tilde{\mathscr{H}}} \rangle$. Here, we propose a new score function ($\mathcal{S}(\tilde{\mathscr{H}})$) on $\tilde{\mathscr{H}}$, as follows,

$$\mathcal{S}(\tilde{\mathscr{H}}) = \text{Score}(\tilde{\mathscr{H}}) = \frac{1}{3}\left(1 + \mu^{3}_{\tilde{\mathscr{H}}} - \nu^{3}_{\tilde{\mathscr{H}}}\right)\left(\mu_{\tilde{\mathscr{H}}} + \nu_{\tilde{\mathscr{H}}}\right) \tag{9}$$

Definition 7. Accuracy functions of DIFN:

Consider, from a Discrete Intuitionistic Fuzzy set $\tilde{\mathscr{H}} = \{(r, \mu_{\mathscr{H}}(r), \nu_{\mathscr{H}}(r)) : r \in \mathbb{R}\}$, we can represent the DIFN $\tilde{\mathscr{H}} = \langle \mu_{\tilde{\mathscr{H}}}, \nu_{\tilde{\mathscr{H}}} \rangle$. Here, we propose a new accuracy function ($\mathcal{A}(\tilde{\mathscr{H}})$) on $\tilde{\mathscr{H}}$, as follows,

$$\mathcal{A}(\tilde{\mathscr{H}}) = \text{Accuracy}(\tilde{\mathscr{H}}) = \frac{1}{3}\left(1 + \mu^3_{\tilde{\mathscr{H}}} - \nu^3_{\tilde{\mathscr{H}}}\right) \tag{10}$$

Theorem 1. Consider $\tilde{\mathscr{I}}$ and $\tilde{\mathscr{J}}$ are two Discrete Intuitionistic Fuzzy Numbers (DIFN) defined on the set of real numbers $(\mathbb{R})$. Then the order relation is defined on DIFNs $\tilde{\mathscr{I}}$ and $\tilde{\mathscr{J}}$ as follows:
1. If $\mathcal{S}(\tilde{\mathscr{I}}) < \mathcal{S}(\tilde{\mathscr{J}})$, then $\tilde{\mathscr{I}} < \tilde{\mathscr{J}}$.
2. If $\mathcal{S}(\tilde{\mathscr{I}}) > \mathcal{S}(\tilde{\mathscr{J}})$, then $\tilde{\mathscr{I}} > \tilde{\mathscr{J}}$.
3. If $\mathcal{S}(\tilde{\mathscr{I}}) = \mathcal{S}(\tilde{\mathscr{J}})$, then
(a) If $\mathcal{A}(\tilde{\mathscr{I}}) < \mathcal{A}(\tilde{\mathscr{J}})$, then $\tilde{\mathscr{I}} < \tilde{\mathscr{J}}$.
(b) If $\mathcal{A}(\tilde{\mathscr{I}}) > \mathcal{A}(\tilde{\mathscr{J}})$, then $\tilde{\mathscr{I}} > \tilde{\mathscr{J}}$.
(c) If $\mathcal{A}(\tilde{\mathscr{I}}) = \mathcal{A}(\tilde{\mathscr{J}})$, then $\tilde{\mathscr{I}} \equiv \tilde{\mathscr{J}}$.

Remark 1. In this research paper, we consider the score function on Discrete Intuitionistic Fuzzy Number (DIFN) to compute the numerical results. If the score function does not provide any conclusion, then the accuracy function applies on the Discrete Intuitionistic Fuzzy Number (DIFN) for numerical evaluation.

4 MCDM Based Entropy Weighted Methodology

In this research work, this section properly explained the mathematical procedure through MCDM methodology [29]. There are several weighted calculated MCDM methods are used for optimization, such as Analytic Hierarchy Process (AHP) [42], Analytic Network Process (ANP) [43], CRiteria Importance Through Inter-criteria Correlation (CRITIC) [44], Entropy [31]; Decision making trial and evaluation laboratory (DEMATEL) [45], Stepwise Weight Assessment Ratio Analysis (SWARA) [46]and many more. It is a standard procedure for evaluating the criteria weight for making decisions in considering multiple conflicting factors. The Entropy named MCDM technique [34], is used here to assess the required outcomes. The approach of the above mentioned method is clarified below.

In 1948, Shannon [33, 47] proposed a mathematical communication theory, naming the Entropy weighted method. Figure 1 repressed the structural flowchart of the Entropy weighted method.

In this research work, l' number of decision makers (DMs) make opinions based on their skills and knowledge. Also, consider that there are m number of criteria and c number of alternatives associated with this model. For each criteria ζ, here, $\zeta = 1, 2, \ldots, m$. The following steps are in the Entropy method:

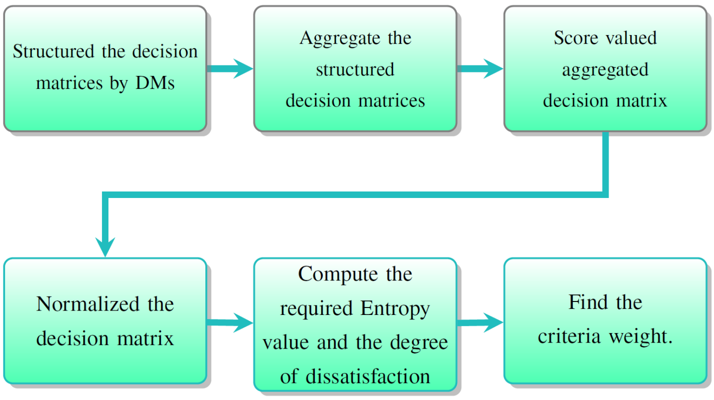

Figure 1. Constructional framework of the Entropy process

I: Structured the decision matrices $\left(\left(\tilde{\mathscr{A}}_m\right)_{\mathcal{D}}\right)$:

First of all, we have established a decision matrix $\left(\left(\tilde{\mathscr{A}}_m\right)_{\mathcal{D}}\right)$ based on the wise opinion of DMs in linguistic terms. This is structured by $\mathcal{D}$-th decision makers (DMs) where, $\mathcal{D} = 1, 2, \ldots, \mathcal{D}, \ldots, l'$ and l' be the total number of decision makers.

$$\left(\tilde{\mathscr{A}}_m\right)_{\mathcal{D}} = \begin{bmatrix} \left(\tilde{\mathscr{E}}_{11}\right)_{\mathcal{D}} & \left(\tilde{\mathscr{E}}_{12}\right)_{\mathcal{D}} & \cdots & \left(\tilde{\mathscr{E}}_{1m}\right)_{\mathcal{D}} \\ \left(\tilde{\mathscr{E}}_{21}\right)_{\mathcal{D}} & \left(\tilde{\mathscr{E}}_{22}\right)_{\mathcal{D}} & \cdots & \left(\tilde{\mathscr{E}}_{2m}\right)_{\mathcal{D}} \\ \vdots & \vdots & \ddots & \vdots \\ \left(\tilde{\mathscr{E}}_{c1}\right)_{\mathcal{D}} & \left(\tilde{\mathscr{E}}_{c2}\right)_{\mathcal{D}} & \cdots & \left(\tilde{\mathscr{E}}_{cm}\right)_{\mathcal{D}} \end{bmatrix} \tag{11}$$

i.e.,

$$\left(\tilde{\mathscr{A}_m}\right)_{\mathcal{D}} = \left[\left(\tilde{\mathscr{E}}_{\eta\zeta}\right)_{\mathcal{D}}\right]_{cm} \tag{12}$$

where, $\left(\tilde{\mathscr{A}_m}\right)_{\mathcal{D}}$ is $c \times m$ order matrix; $\mathcal{D} = 1, 2, \ldots, l'$; each alternatives η (when, $\eta = 1, 2, \ldots, c$) and each criteria ζ (when, $\zeta = 1, 2, \ldots, m$).

II: Aggregation the structured decision matrices $\left(\tilde{\mathscr{A}_m}\right)$:

The above decision matrices aggregate into a decision matrix $\left(\tilde{\mathscr{A}_m}\right)$,

$$\begin{aligned} \chi 1_{\tilde{\delta}_{\zeta\nu}} &= \left\{\mu_{\tilde{\delta}_{\zeta\nu}}, \nu_{\tilde{\delta}_{\zeta\nu}}\right\} \\ &= \left\{\min_{\mathcal{D}=1,2,\ldots,l'} \left(\mu_{\tilde{\delta}_{\zeta\nu}}\right)_{\delta}, {}_{\mathcal{D}=1,2,\ldots,l'} \left(\nu_{\tilde{\delta}_{\zeta\nu}}\right)_{\delta}\right\} \end{aligned} \tag{13}$$

The aggregated decision matrix $\left(\tilde{\mathscr{A}_m}\right)$ is constructed from Eq. (11) using Eq. (13). So, the aggregated decision matrix $\left(\tilde{\mathscr{A}_m}\right)$ for criteria, denoted as $\tilde{\mathscr{F}}_e$, i.e.,

$$\tilde{\mathscr{A}_m} = \left[\tilde{\mathscr{E}}_{\eta\zeta}\right]_{\text{cm}} \tag{14}$$

III: Score valued aggregated decision matrix $\left(\tilde{\mathscr{A}_s}\right)$:

Using the score function $\left(\mathcal{S}\left(\tilde{\mathscr{E}_s}\right)\right)$ of the DIFNs are converted to a crisp number and so the score valued decision matrix $\left(\tilde{\mathscr{A}_s}\right)$ is formulated as follows,

$$\tilde{\mathscr{A}_m} = \left[\tilde{\mathscr{E}}_{\eta\zeta}\right]_{\text{cm}} \tag{15}$$

where, $\left(\tilde{\mathscr{E}_s}\right)_{\eta\zeta}$ is the score value of DIFN $\tilde{\mathscr{E}}_{\eta\zeta}$ calculated by Eq. (9).

IV: Normalized the decision matrix $\left(\tilde{\mathscr{A}_n}\right)$:

To formulate a Normalized decision matrix $\left(\tilde{\mathscr{A}_n}\right)$ from the score valued decision matrix $\left(\tilde{\mathscr{A}_s}\right)$, we use the following formula,

$$\tilde{\mathscr{E}}^{k}_{\eta\zeta} = \frac{\tilde{\mathscr{E}}_{\eta\zeta}}{\sum_{\eta=1}^{c} \tilde{\mathscr{E}}_{\eta\zeta}} \tag{16}$$

V: Calculate the required entropy value $(\mathscr{Y}'_{\zeta})$:

Evaluate the entropy value $(\mathscr{Y}'_{\zeta})$ of each criteria using Eq (16), we get,

$$\mathscr{Y}'_{\zeta} = -\frac{1}{\log c} \times \sum_{\eta=1}^{c} \left\{\tilde{\mathscr{E}}^{k}_{\eta\zeta} \times \log\left(\tilde{\mathscr{E}}^{k}_{\eta\zeta}\right)\right\} \tag{17}$$

where, $\eta = 1, 2, \ldots, c$ and $\zeta = 1, 2, \ldots, m$.

VI: Compute the degree of dissatisfaction $(\mathscr{G}_{\zeta})$:

The degree of dissatisfaction $(\mathscr{G}_{\zeta})$ for each criteria μ, e|valuated by Eq. (18), as follows:

$$\mathscr{G}_{\zeta} = (1 - \mathscr{Y}'_{\zeta}) \tag{18}$$

where, $\zeta = 1, 2, \ldots, m$.

VII: Criteria weight $(\mathcal{W}_{\zeta})$:

The required criteria weight $(\mathcal{W}_{\zeta})$ is find out by Equation (19), as follows:

$$\mathcal{W}_{\zeta} = \frac{\mathscr{G}_{\zeta}}{\sum_{\zeta=1}^{m} \mathscr{G}_{\zeta}} \tag{19}$$

The evaluated criteria weight $(\mathcal{W}_{\zeta})$ from Eq. (19), which is used for further calculation, where $\zeta = 1, 2, \ldots, m$. Eq. (19) shows the weight of criteria by the Entropy weighted method.

Remark 2. In this work, we only consider the seven important criteria for calculating the factor weight to determine the most effective challenges for wireless communication technology.

4.1 Pseudo Code of This Empirical Model

This section describes the Pseudo code [48] of this proposed study. Establish the framework with m number of criteria, c number of alternatives and l' number of decision makers (DMs) consider for constructing the model. The decision matrix is built with $c \times m$ order for criteria. The MCDM technique, namely Entropy, is applied to determine the criteria weights. The l' number of $c \times m$ order decision matrix for criteria is taken as input data. The pseudo code of this model is:

Input: l' number of $c \times m$ order decision matrix for criteria
Output: Calculate criteria weight
Compute: Local and global weights of the criteria
Initialize: Linguistic terms and crisp numbers
Operation: Entropy

1. **Merge** Aggregate the l' number of decision matrices for criteria
2. **Normalization** normalize the aggregated decision matrix
3. **For Entropy**
4. **Find** determine the logarithmic value for every entry
5. **Then** evaluate the logarithmic sum for every criteria
6. **Calculate** find out the entropy value and degree of dissatisfaction value
7. **Find** determine the weights of the criteria
8. **End Entropy**

5 Criteria Selection

This section describes the short description of every criterion. Determine the most effective challenges for wireless communication technology is dependent on multiple criteria. Those criteria are chosen from the detailed literature studies, i.e., [1–5, 13–19] and opinions taken from two wise decision makers (DMs). Seven criteria are considered for this work. The short discussion on these criteria is mentioned below.

(a) Scalability $(\mathscr{D}_1)$: Scalability [49] is a key challenge for wireless communication technology, focusing on controlling the rising number of connected devices while mounting data traffic. While maintaining the performance, future systems must support various IoT devices, which is very important for innovative resource allocation, density of network and scalability of cloud-based solutions. Identifying scalability [50] ensures smooth connectivity and experience of the user across diverse environments. Further, it prepares networks for overseeing evolving technologies, i.e., 5G and beyond.

(b) Efficiency of Energy $(\mathscr{D}_2)$: Energy efficiency [51] is a crucial challenge for wireless communication technology, that aims to minimise power usage while maintaining performance. Low-power design is vital mainly for IoT devices and battery-powered systems, which gain efficiency through techniques, such as energy harvesting, sleep modes and optimized transmission protocols. Determining this challenge guarantees longer device lifespans and sustainable operations. It also helps to reduce the operational costs in wireless networks.

(c) Applying Spectrum $(\mathscr{D}_3)$: A major obstacle for wireless communication technology is proper spectrum [52] utilisation, which addresses making the most of the limited frequency resources. Advanced techniques, i.e., dynamic spectrum and cognitive radio access, help to increase sharing, efficient allocation and reuse of spectrum by enabling smarter utilisation. Fixing this challenge ensures elevated network connectivity and supports emerging technologies like IOT and 5G. Moreover, it inhibits interference and improves the reliability of total communication [53].

(d) Interference Management and Costs $(\mathscr{D}_4)$: Managing interference [54] and lowering deployment and operational costs are significant challenges to ensure reliable wireless communication in dense atmospheres. Advanced techniques, such as signal filtering, beamforming and dynamic frequency selection are necessary for alleviating interference. And, the growth of cost-effective infrastructure solutions,i.e., small cells and shared networks, is important. Dealing with interference is tough for supporting seamless connectivity while scaling capacity with advances in next-generation technologies like 5G.

(e) Latency and Security $(\mathscr{D}_5)$: Creating certain latency and strong security is extremely important to make sure the wireless communication systems are protected from different cyber threats, unauthorized access, data breaches, etc., by hampering latency for applications, such that AR/VR that enable real-time wireless communication. On the one hand, advanced measures, such as quantum encryption and AI-based monitoring, develop network resilience. On the other hand, techniques like edge computing, network slicing and optimized routing help diminish latency [55]. Dealing with this challenge supports the progress of next-generation technologies by addressing security while keeping critical data secure and strengthening user experience.

(f) Compatibility and Emerging Use Cases $(\mathscr{D}_6)$: Ensuring compatibility is a big obstacle as wireless networks adapt to seamlessly integrate with already existing infrastructure. In addition, things, i.e., AR/VR, smart cities and IoT represent newrequirements on wireless systems for a variety of emerging use cases [56]. Compatibility with unified addressing quits fragmentation and promotes user satisfaction while technology upgrades. It is vital to design scalable networks for diverse applications that require higher data rates, ultra-low latency, and improved reliability.

(g) Environmental Effect ($\mathscr{D}_7$) : Eliminating the environmental effects of wireless communication technology is a rising challenge nowadays. Energy-efficient designs and renewable energy sources are important to trim the carbon footprint of network operations. E-waste from devices and infrastructure can be mitigated by recycling and environmentally friendly production processes. Innovations, s.t., green network deployments and energy harvesting support the eco-friendly operations. Identifying this issue guarantees sustainable growth while balancing technological advancements with preserving the environment [57].

6 Alternative Selection

This section describes the alternative selection procedure in detail. Alternatives of wireless communication technologies are considered by the study on different research, including [1–5, 14–18]. Here we use different wireless communication technologies as alternatives.

i). Infrared (IR) ($\mathscr{B}_1$): Infrared (IR) is a particular type of electromagnetic radiation that has wavelengths longer than visible light but shorter than microwaves. It is frequently applied in different applications, i.e., remote controls, thermal imaging and communication systems. Infrared radiation is tied with heat, as it is released by warm substances. It has an important role in everyday technologies, like astronomy, medicine, etc.

ii). Zigbee ($\mathscr{B}_2$): Alow-power, wireless communication technology structured for Internet of Things (IoT) devices is known as Zigbee. It works on a mesh network, with the connected devices to communicate efficiently over short to medium distances. Zigbee is widely applied in industrial automation, smart home systems and healthcare devices. Its devotion to energy efficiency and reliability makes it perfect and proper for battery-used applications.

iii). Cellular Networks (4G/5G) ($\mathscr{B}_3$): Cellular networks, s.t., 4G and 5G enable wireless communication for mobile applications and it support the high-speed internet and data services. 4G gives the offer of superfast connectivity, that is suitable for streaming and browsing, and 5G increases the speed, reduces latency, and enables advanced systems like IoT and augmented reality. These networks are vital for contemporary technology and communication.

iv). Bluetooth ($\mathscr{B}_4$): Bluetooth is a popular wireless communication technology adopted for short-range data exchange between two devices. It is extensively used for connecting supplementary, i.e., headphones, keyboards, smartphones, without the need for any cables. It is energy-efficient and can support different applications, including important file transfer, audio streaming and IoT connectivity.

v). Near Field Communication (NFC) ($\mathscr{B}_5$): A short-range wireless technology that allows devices to exchange data within a few centimeters is known as Near Field Communication (NFC). It is mainly used for access control, contactless payments and quick data sharing between smart devices. NFC is a safe, convenient, and expanding integration into modern technologies.

vi). Wi-Fi ($\mathscr{B}_6$): Wi-Fi is a widely utilised wireless networking technology that permits devices to communicate with the internet and communicate over the local area network (LAN). It applies radio waves to supply high-speed data transfer, which is typically used in homes, offices, and public spaces. Wi-Fi is important for seamless connectivity and it supports the vast range of applications.

vii). LoRaWAN ($\mathscr{B}_7$): A low-power, wireless communication protocol structured for long-range connectivity in IoT devices is called LoRaWAN (Long RangeWide Area Network). It serves on unlicensed radio frequencies, enabling devices to transfer small datasets over distances up to various kilometers. LoRaWAN is perfect for agriculture, smart cities and industrial monitoring for the reason of its scalability and energy efficiency.

7 Application of Decision Making Framework

This section first discussed the model structure of this study, followed by the data collection procedure and data sources of this research in detail. Lastly, the results and discussion of this study are discussed elaborately in this section. The model formulation of this proposed study is presented as follows:

7.1 Model Structured

This section structured the proposed model in detail. The seven most beneficial criteria for determining the potent challenges for wireless communication technology are chosen from a detailed literature review and the decision makers' (DMs) perspective. Further, seven alternatives are considered for this wireless communication technology adaptation by considering various wireless communication research articles. All the criteria and alternatives are selected through detailed literature studies and the decision makers' opinions. Then, the decision matrix is evaluated with a 7 × 7 order matrix for data collection for numerical evaluation. Section 5 and Section 6 discuss on the criteria and alternatives of wireless communication technology, respectively. The structural flowchart of the effective challenges for wireless communication technology is shown in Figure 2.

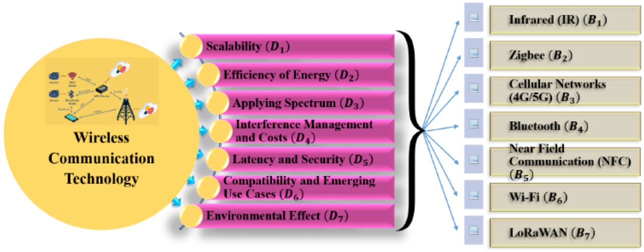

Figure 2. Hierarchical structure of the most effective challenges for wireless communication technology

7.2 Data Collection

Data source and data collection procedure are thoroughly discussed in this section. All the data are collected from two decision makers (DMs), who are knowledgeable, professional, experienced and unbiased in their fields. The DMs are given data in linguistic terms and it is converted into DIFNs using Table 1. Details about DMs as follows:

DM1: A computer engineer with 20 years of experience.

DM2: A professor works in computer science engineering fields.

Model structured Table 1 represents the conversion matrix between linguistic terms and Discrete Intuitionistic Fuzzy Number (DIFN). The data are given in decision matrix form in Table 2 in linguistic terms and decoded using Table 1. This data are further used in the numerical evaluation later section.

Table 1. Conversion table between linguistic term and DIFN

Linguistic Terms	Discrete Intuitionistic Fuzzy Number (DIFN)	Score Value
Severe Important (SI)	$\langle 0.55, 0.10\rangle$	0.25
Very Important (VI)	$\langle 0.50, 0.12\rangle$	0.23
Moderately Important (MI)	$\langle 0.45, 0.14\rangle$	0.21
Equally Important (EI)	$\langle 0.40, 0.16\rangle$	0.19
Weekly Important (WI)	$\langle 0.35, 0.18\rangle$	0.18
Below Important (BI)	$\langle 0.30, 0.20\rangle$	0.17
Low Important (LI)	$\langle 0.25, 0.22\rangle$	0.16

7.3 Numerical Illustration and Discussion

This section talks about the required numerical result evaluated by the Entropy process and then tests the results. Seven criteria are taken for evaluation elaborately, which have already been discussed in Section 5 and seven alternatives are considered to determine the required results discussed elaborately in Section 6, respectively. The MCDM based decision making technique, namely the Entropy weighted method, explained in Section 4 is used for numerical formulation. Needed data are collected from Section 7.2 and changed into the DIFNs for numerical evaluation.

In this uncertain environment, we consider the data from the two DMs in linguistic terms and it is formulated in the decision matrices in Table 2 at first. Then, we calculate the criteria weights using the Entropy weighted method, which is shown in Table 3.

The Entropy weighted method utilized the criteria weights by following steps. First, structured the decision matrix $\left(\left(\tilde{\mathscr{A}_m}\right)_{\mathcal{D}}\right)$ by Eq. (11) from Table 2 and applied for further numerical procedure. Then the two DMs data are aggregated to one aggregated decision matrix $\left(\tilde{\mathscr{A}_m}\right)$ by using Eq. (13). Further, the score valued aggregated decision matrix $\left(\tilde{\mathscr{A}_s}\right)$ formulated from the aggregated decision matrix $\left(\tilde{\mathscr{A}_m}\right)$ using Eq. (9). Then, normalized the decision matrix $\left(\tilde{\mathscr{A}_n}\right)$ by using Eq. (16). Further, determine the entropy value $\left(\mathscr{Y}_\zeta^{\prime}\right)$ and the degree of dissatisfaction value $(\mathscr{G}_\zeta)$ of each criteria ζ by using Eq. (17) and Eq. (18), respectively. Finally, the required criteria weight $(\mathcal{W}_\zeta)$ are calculated for each criteria ζ using Eq. (19). The weights of the criteria determined by Entropy weighted method for this wireless communication technology are presented in Table 3.

Table 3 presents theweight of given criteria to determine the most effective challenges for wireless communication technology. Moreover, Figure 3 shows this graphically through the Pi diagram.

Table 2. Decision matrix constructed in linguistic terms by two DMs

	Criteria vs Alternatives	Scalability ($\mathscr{D}_1$)	Efficiency of Energy ($\mathscr{D}_2$)	Applying Spectrum ($\mathscr{D}_3$)	Interference Management and Costs ($\mathscr{D}_4$)	Latency and Security ($\mathscr{D}_5$)	Compatibility and Emerging Use Cases ($\mathscr{D}_6$)	Environmental Effect ($\mathscr{D}_7$)
DM_1	Infrared (IR) ($\mathscr{B}_1$)	WI	MI	EI	VI	MI	BI	MI
	Zigbee ($\mathscr{B}_2$)	EI	VI	SI	MI	MI	MI	SI
	Cellular Networks (4G/5G) ($\mathscr{B}_3$)	SI	MI	VI	LI	VI	EI	BI
	Bluetooth ($\mathscr{B}_4$)	SI	EI	MI	MI	BI	VI	MI
	Near Field Communication (NFC) ($\mathscr{B}_5$)	BI	MI	WI	EI	BI	BI	SI
	Wi-Fi ($\mathscr{B}_6$)	VI	SI	SI	VI	MI	VI	EI
	LoRaWAN ($\mathscr{B}_7$)	BI	WI	LI	WI	EI	MI	VI
DM_2	Infrared (IR) ($\mathscr{B}_1$)	BI	VI	EI	MI	VI	WI	MI
	Zigbee ($\mathscr{B}_2$)	EI	SI	VI	MI	SI	VI	VI
	Cellular Networks (4G/5G) ($\mathscr{B}_3$)	VI	VI	SI	WI	SI	EI	WI
	Bluetooth ($\mathscr{B}_4$)	SI	EI	VI	MI	LI	SI	VI
	Near Field Communication (NFC) ($\mathscr{B}_5$)	LI	MI	BI	EI	LI	BI	VI
	Wi-Fi ($\mathscr{B}_6$)	SI	VI	VI	SI	VI	SI	EI
	LoRaWAN ($\mathscr{B}_7$)	BI	LI	BI	BI	EI	MI	MI

Table 3. Criteria weight evaluated by Entropy method

Criteria	Weight
Scalability ($\mathscr{D}_1$)	0.232
Efficiency of Energy ($\mathscr{D}_2$)	0.106
Applying Spectrum ($\mathscr{D}_3$)	0.161
Interference Management and Costs ($\mathscr{D}_4$)	0.126
Latency and Security ($\mathscr{D}_5$)	0.154
Compatibility and Emerging Use Cases ($\mathscr{D}_6$)	0.148
Environmental Effect ($\mathscr{D}_7$)	0.073

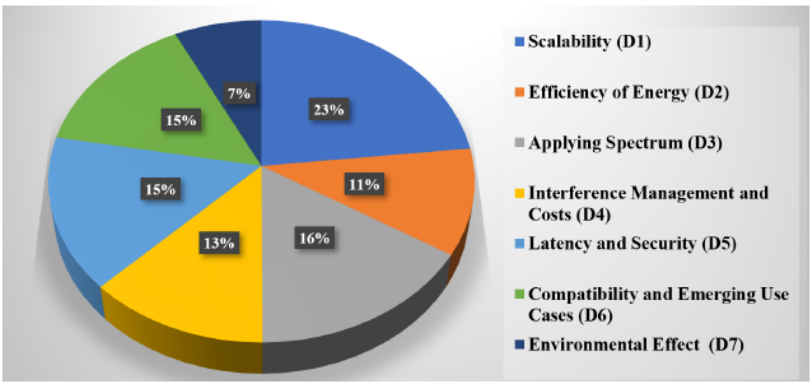

Figure 3. Pi diagram of the criteria weight applying Entropy methodology

Remark 3. Table 3 and Figure 3 represent the criteria weight of the criteria and graphical structure of it through the Pi diagram using Entropy based MCDM methodology. From the above result, criteria Scalability ($\mathscr{D}_1$) get the optimal weight with weighted value 0.232 and Applying Spectrum ($\mathscr{D}_3$) get the secohd optimal weighted value with 0.161 score. Then criteria Latency and Security ($\mathscr{D}_5$) get the third highest weighted value with 0.154 score and criteria Compatibility and Emerging Use Cases ($\mathscr{D}_6$) get fourth highest weighted value with 0.148 score, respectively.

The criteria Interference Management and Costs ($\mathscr{D}_4$) and Efficiency of Energy ($\mathscr{D}_2$) get fifth and sixth optimal value with 0.126 and 0.106 weighted values, respectively. Lastly, Environmental Effect ($\mathscr{D}_7$) gets the least weighted values 0.073 by the Entropy weight method.

8 Sensitivity Analysis

This section discussed the sensitivity analysis of this proposed model. There are three cases conducted to perform this sensitive analysis. The cases are described as follows:

(A) Case 1: Removing criteria Efficiency of Energy ($\mathscr{D}_2$) : Sensitivity analysis performed by removing criteria Efficiency of Energy ($\mathscr{D}_2$). This criterion is one of the important criteria with weight 0.106 . In sensitivity analysis, we remove the criteria and evaluate the weight of the remaining criteria by the Entropy weighted method. The weight of the criteria is presented in Figure 4 compared with the proposed method.

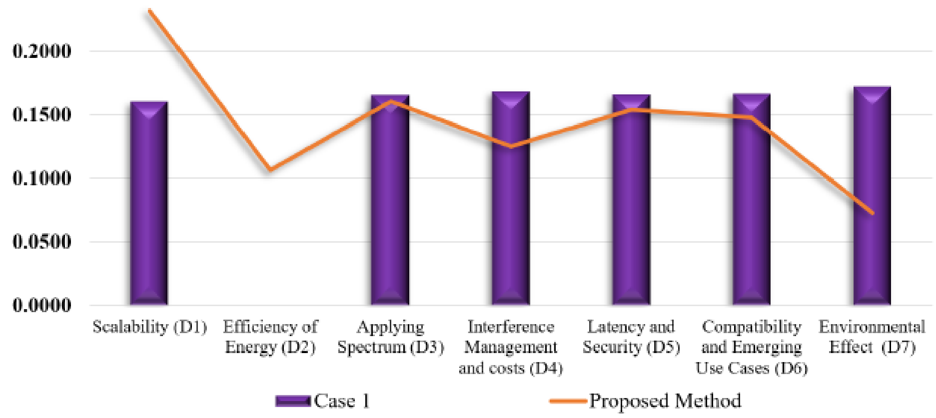

Figure 4. Comparative weight analysis by removing criteria Efficiency of Energy $\mathscr{D}_2$

(B) Case 2: Removing criteria Interference Management and Costs ($\mathscr{D}_4$) : In the second case, sensitivity analysis conducted by removing the fourth criteria, namely Interference Management and Costs ($\mathscr{D}_4$). It is one of the most significant criteria with weight value 0.126 by the Entropy weighted method. Here, we remove the criteria and calculate the weight of the remaining criteria by this MCDM based method. The weight of the criteria is shown in Figure 5 compared with the proposed method.

(C) Case 3: Removing criteria Environmental Effect ($\mathscr{D}_7$) : In the third sensitivity analysis case performed by removing the criteria Environmental Effect ($\mathscr{D}_7$). It is the least weighted criteria with the weighted value 0.073 by the Entropy weighted method. In this case, we evaluated the criteria weight by considering the first six criteria and the results are shown in Figure 6 compared with the proposed method.

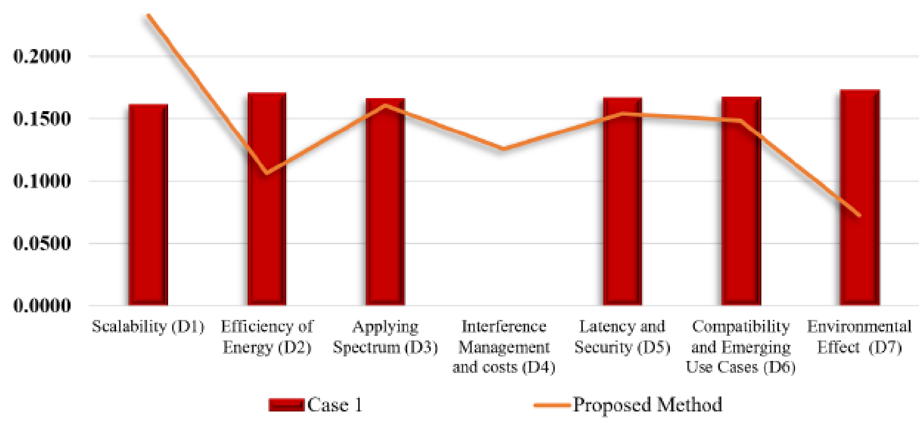

Figure 5. Comparative weight analysis by removing criteria Interference Management and Costs ($\mathscr{D}_4$)

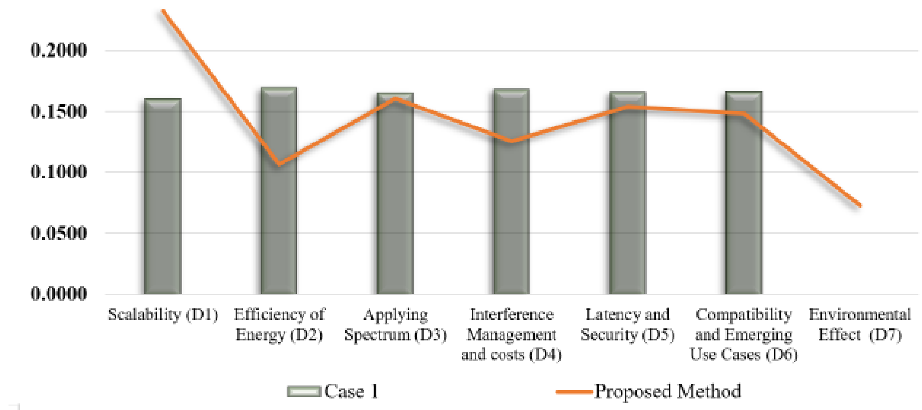

Figure 6. Comparative weight analysis by removing criteria Environmental Effect ($\mathscr{D}_7$)

9 Conclusions, Research Implication and Future Research Scope

In brief, determining the most effective challenges for wireless communication technology is crucial for modifying connectivity and noble innovation. Researchers can enhance the performance of the network and scalability by handling various problems including energy efficiency, security threats and spectrum scarcity. Solutions to these difficulties support the growth of future technologies, such as 6G and IoT, while boosting user experience with the accessibility. Furthermore, managing these hurdles ensures safe and secure wireless systems. Interdisciplinary collaboration is essential for crafting comprehensive solutions. And ultimately, this research work drives technological development and enables the world that is more connected.

To determine the most effective challenges for wireless communication technology has important research implications in a number of areas. First of all, addressing different kinds of difficult challenges (i.e., energy efficiency, spectrum scarcity, latency and security, etc.) assists in guiding the innovative ideas and enhancing the speed and reliability of wireless communication technology. Research can help to find the solutions for handling the increasing number of connected devices in 5G, IoT, etc., assuring the sturdy communication networks. Identifying several issues like signal quality, interference and flawless connectivity, etc. can expand the experience and satisfaction of the user. And finally,economic growth can be facilitated by finding solutions to wireless challenges that lower costs, increase accessibility and open new markets.

This research paper has some study limitations, i.e., a limited number of decision-makers, specify more wireless devices and presumptions made during model formulation, etc. This related research can be developed in the future to overcome these limitations. Only seven criteria are selected for this paper, which may extend to choose all less significant criteria and get more appropriate results. And also, one can consider sub-criteria for every criterion to evaluate this work with more clarity. In the future, one can find the rank of the selected alternative with several ranking MCDM methods. This paper may extend by choosing different MCDM processes, like the AHP weighted method, SWARA method, CRITIC method, etc. Various fuzzy numbers can be selected as uncertainty tools, such as Neutrosophic fuzzy numbers, Pythagorean fuzzy numbers, etc. Comparative analysis may be conducted to verify stability and vagueness of the system. May concern different formulas for finding the score value to analyze the accuracy of the results. Besides, more wise decision makers may consider finding the required error free data.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] C. Prakash, L. P. Singh, A. Gupta, and S. K. Lohan, "Advancements in smart farming: A comprehensive review of IOT, wireless communication, sensors, and hardware for agricultural automation," *Sens. Actuators A Phys.*, vol. 362, no. 114605, 2023. https://doi.org/10.1016/j.sna.2023.114605

[2] M. Yücela and M. Açikgöz, "Optical communication infrastructure in new generation mobile networks," *Fiber Integr. Opt.*, vol. 42, no. 2, pp. 53–92, 2023. https://doi.org/10.1080/01468030.2023.2186811

[3] W. Aman, S. Al-Kuwari, M. Muzzammil, M. M. U. Rahman, and A. Kumar, “Security of underwater and air–water wireless communication: State-of-the-art, challenges and outlook,” *Ad Hoc Netw.*, vol. 142, no. 103114, 2023. https://doi.org/10.1016/j.adhoc.2023.103114

[4] A. A. Amin, J. Hong, V.-H. Bui, and W. Su, “Emerging 6g/b6g wireless communication for the power infrastructure in smart cities: Innovations, challenges, and future perspectives,” *Algorithms*, vol. 16, no. 10, p. 474, 2023. https://doi.org/10.3390/a16100474

[5] X. Gu and G. Zhang, “A survey on UAV-assisted wireless communications: Recent advances and future trends,” *Comput. Commun.*, vol. 208, pp. 44–78, 2023. https://doi.org/10.1016/j.comcom.2023.05.013

[6] A. Siekelova, I. Podhorska, and J. J. Imppola, “Analytic hierarchy process in multiple–criteria decision–making: A model example,” *Results Control Optim.*, vol. 90, p. 01019, 2021. https://doi.org/10.1016/j.rico.2021.01019

[7] I. Hassan, I. Alhamrouni, and N. H. Azhan, “A CRITIC–TOPSIS multi-criteria decision-making approach for optimum site selection for solar pv farm,” *Energies*, vol. 16, no. 10, p. 4245, 2023. https://doi.org/10.3390/en16104245

[8] H. Taherdoost and A. Mohebi, “A comprehensive guide to the copras method for multi-criteria decision making,” *J. Manag. Sci. Eng. Res.*, vol. 7, no. 2, pp. 1–14, 2024.

[9] A. Hafezalkotob, A. Hafezalkotob, H. Liao, and F. Herrera, “An overview of MULTIMOORA for multi-criteria decision-making: Theory, developments, applications, and challenges,” *Inf. Fusion*, vol. 51, pp. 145–177, 2019. https://doi.org/10.1016/j.inffus.2018.12.002

[10] A. M. Ghaleb, H. Kaid, A. Alsamhan, S. H. Mian, and L. Hidri, “Assessment and comparison of various MCDM approaches in the selection of manufacturing process,” *Adv. Mater. Sci. Eng.*, no. 1, p. 4039253, 2020. https://doi.org/10.1155/2020/4039253

[11] J. Guo, X. Zhu, K. You, Z. Wang, Q. Wang, and H. Li, “A proportional fuzzy elimination and choice translating reality II method for multicriteria decision-making problems: A robust new methodology for practical applications,” *IEEE Syst. Man Cybern. Mag.*, vol. 10, no. 3, pp. 22–30, 2024. https://doi.org/10.1109/MSMC.2023.3241426

[12] B. Uzun, A. Almasri, and D. Uzun Ozsahin, “Preference ranking organization method for enrichment evaluations (promethee),” in *Multi-Criteria Decision Making*. Springer, 2021, vol. 336, pp. 37–41. https://doi.org/10.1007/978-3-030-64765-0_6

[13] M. Sengaliappan and K. Kumaravel, “Analysis study of wireless technology and its communication standards using IEEE 802.11,” *Int. J. Adv. Res. Sci. Eng. Technol.*, vol. 4, no. 6, 2017.

[14] F. Li and C. Wang, “Artificial intelligence and edge computing for teaching quality evaluation based on 5g-enabled wireless communication technology,” *J. Cloud Comput.*, vol. 12, no. 1, p. 45, 2023. https://doi.org/10.1186/s13677-023-00418-6

[15] M. Theissen, L. Kern, T. Hartmann, and E. Clausen, “Use-case-oriented evaluation of wireless communication technologies for advanced underground mining operations,” *Sensors*, vol. 23, no. 7, p. 3537, 2023. https://doi.org/10.3390/s23073537

[16] R. R. Chandan, A. Balobaid, N. L. S. Cherukupalli, G. H. L., F. Flammini, and R. Natarajan, “Secure modern wireless communication network based on blockchain technology,” *Electronics*, vol. 12, no. 5, p. 1095, 2023. https://doi.org/10.3390/electronics12051095

[17] Y. Su, Y. Lin, S. Liu, M. Liwang, X. Liao, and T. Wu, “Coexistence of hybrid VLC-RF and Wi-Fi for indoor wireless communication systems: An intelligent approach,” *IEEE Trans. Netw. Serv. Manag.*, vol. 21, no. 6, pp. 6465–6479, 2024. https://doi.org/10.1109/TNSM.2024.3436887

[18] S. Sharma, D. Yadav, G. K. Soni, and G. Shankar, “Operational transconductance amplifier for Bluetooth/WiFi applications using CMOS technology,” in *2024 International Conference on Integrated Circuits and Communication Systems (ICICACS)*, Bengaluru, India, 2024, pp. 1–4. https://doi.org/https://doi.org/10.1109/ICICACS60521.2024.10499107

[19] M. Islam and S. J. Jin, “An overview research on wireless communication network,” *Adv. Wirel. Commun. Netw.*, vol. 5, no. 1, pp. 19–28, 2019. https://doi.org/10.11648/j.awcn.20190501.13

[20] S. Yan, “Research on the applications of the wireless communication,” *Appl. Comput. Eng.*, vol. 40, no. 1, pp. 192–198, 2024. https://doi.org/10.54254/2755-2721/40/20230649

[21] S. Gupta, “Wireless communication,” *Int. J. Sci. Eng.*, vol. 3, no. 8, 2012.

[22] S. Man, B. C. Saw, A. Bairagi, and S. B. Hazra, “Finite difference method for intuitionistic fuzzy partial differential equations,” *Comput. Sci. Math. Forum*, vol. 7, no. 1, p. 48, 2023. https://doi.org/10.3390/IOCMA2023-14406

[23] V. A. Khan, E. E. Kara, H. Altaf, N. Khan, and M. Ahmad, “Intuitionistic fuzzy I-convergent Fibonacci difference sequence spaces,” *J. Inequal. Appl.*, vol. 2019, no. 202, pp. 1–7, 2019. https://link.springer.com/article/10.1186/s13660-019-2152-1

[24] D. Adhikari, K. H. Gazi, A. Sobczak, B. C. Giri, S. Salahshour, and S. P. Mondal, "Ranking of different states in india based on sustainable women empowerment using MCDM methodology under uncertain environment," *J. Uncertain. Syst.*, vol. 17, no. 4, p. 2450010, 2024. https://doi.org/10.1142/S1752890924500107

[25] Muneeza, S. Abdullah, M. Qiyas, and M. A. Khan, "Multi-criteria decision making based on intuitionistic cubic fuzzy numbers," *Granular Comput.*, vol. 7, pp. 217–227, 2022. https://doi.org/10.1007/s41066-021-00261-7

[26] A. V. Raj and V. Nandhini, "Application of intuitionistic pentagonal fuzzy number in neural network," *J. Emerg. Technol. Innov. Res.*, vol. 4, no. 4, pp. 149–154, 2016.

[27] C. Favi, M. Marconi, M. Mandolini, and M. Germani, "Sustainable life cycle and energy management of discrete manufacturing plants in the Industry 4.0 framework," *Appl. Energy*, vol. 312, no. 118671, 2022. https://doi.org/10.1016/j.apenergy.2022.118671

[28] A. M. Armanuos, K. A. Elgaafary, and T. A. Gado, "Landfill site selection using MCDM methods and GIS in the central part of the Nile Delta, Egypt," *Environ. Monit. Assess.*, vol. 195, no. 12, p. 1407, 2023. https://doi.org/10.1007/s10661-023-11946-8

[29] A. F. Momena, K. H. Gazi, and S. P. Mondal, "Multi-criteria decision analysis for sustainable medicinal supply chain problems with adaptability and challenges issues," *Logistics*, vol. 9, no. 1, p. 31, 2025. https://doi.org/10.3390/logistics9010031

[30] M. U. Cilek, E. D. Guner, and S. Tekin, "The combination of fuzzy analytical hierarchical process and maximum entropy methods for the selection of wind farm location," *Environ. Sci. Pollut. Res.*, vol. 29, pp. 65 391–65 406, 2022. https://doi.org/10.1007/s11356-022-20405-9

[31] W. H. Lam, W. S. Lam, K. F. Liew, and P. F. Lee, "Decision analysis on the financial performance of companies using integrated entropy-fuzzy TOPSIS model," *Mathematics*, vol. 11, no. 2, p. 397, 2023. https://doi.org/10.3390/math11020397

[32] W. Khan, S. Khan, A. Dhamija, M. Haseeb, and S. A. Ansari, "Risk assessment in livestock supply chain using the MCDM method: A case of emerging economy," *Environ. Sci. Pollut. Res.*, vol. 30, no. 8, pp. 20 688–20 703, 2023. https://doi.org/10.1007/s11356-022-23640-2

[33] C. E. Shannon, "A mathematical theory of communication," *Bell Syst. Tech. J.*, vol. 27, no. 3, pp. 379–423, 1948. https://doi.org/10.1002/j.1538-7305.1948.tb01338.x

[34] S. A. I. Hussain and U. K. Mandal, "Entropy based MCDM approach for selection of material," in *National Level Conference on Engineering Problems and Application of Mathematics*, 2016, pp. 1–6.

[35] K. H. Gazi, A. F. Momena, S. Salahshour, S. P. Mondal, and A. Ghosh, "Synergistic strategy of sustainable hospital site selection in Saudi Arabia using spherical fuzzy MCDM methodology," *J. Uncertain. Syst.*, vol. 17, no. 3, p. 2450004, 2024. https://doi.org/10.1142/S1752890924500041

[36] T. Midrar, S. Khan, S. Abdullah, and T. Botmart, "Entropy based extended topsis method for mcdm problem with fuzzy credibility numbers," *AIMS Math.*, vol. 7, no. 9, pp. 17 286–17 312, 2022. https://doi.org/10.3934/math.2022952

[37] L. A. Zadeh, "Fuzzy sets," *Inf. Control*, vol. 8, no. 3, pp. 338–353, 1965. https://doi.org/10.1016/S0019-9958(65)90241-X

[38] M. Woźniak, A. Zielonka, and A. Sikora, "Driving support by type-2 fuzzy logic control model," *Expert Syst. Appl.*, vol. 207, no. 117798, 2022. https://doi.org/10.1016/j.eswa.2022.117798

[39] K. Atanassov and G. Gargov, "Interval valued intuitionistic fuzzy sets," *Fuzzy Sets Syst.*, vol. 31, no. 3, pp. 343–349, 1989.

[40] D. Pamucar, M. Deveci, D. Schitea, L. Erişkin, M. Iordache, and I. Iordache, "Developing a novel fuzzy neutrosophic numbers based decision making analysis for prioritizing the energy storage technologies," *Int. J. Hydrogen Energy*, vol. 45, no. 43, pp. 23 027–23 047, 2020. https://doi.org/10.1016/j.ijhydene.2020.06.016

[41] M. Rahaman, D. Chalishajar, K. H. Gazi, S. Alam, S. Salahshour, and S. P. Mondal, "Fractional calculus for type 2 interval-valued functions," *Fractal Fract.*, vol. 9, no. 102, 2025. https://doi.org/10.3390/fractalfract9020102

[42] M. R. Islam, M. T. Aziz, M. Alauddin, Z. Kader, and M. R. Islam, "Site suitability assessment for solar power plants in bangladesh: A GIS-based analytical hierarchy process (AHP) and multi-criteria decision analysis (MCDA) approach," *Renew. Energy*, vol. 220, p. 119595, 2024. https://doi.org/10.1016/j.renene.2023.119595

[43] H. Taherdoost and M. Madanchian, "Analytic network process (ANP) method: A comprehensive review of applications, advantages, and limitations," *J. Data Sci. Intell. Syst.*, vol. 1, no. 1, pp. 12–18, 2023. https://doi.org/10.47852/bonviewJDSIS3202885

[44] A. F. Momena, K. H. Gazi, M. Rahaman, A. Sobczak, S. S. S. P. Mondal, and A. Ghosh, "Ranking and challenges of supply chain companies using MCDM methodology," *Logistics*, vol. 8, no. 3, p. 87, 2024. https://doi.org/10.3390/logistics8030087

[45] J. Xuefeng, L. Cunbin, and Z. Ying, "Risk identification and influence analysis model for urban energy internet

based on knowledge graph improved decision-making trial and evaluation laboratory," *Expert Syst. Appl.*, vol. 233, no. 120997, 2023. https://doi.org/10.1016/j.eswa.2023.120997

[46] C. B. Karakuş, "Groundwater potential assessment based on GIS-based best–worst method (BWM) and step-wise weight assessment ratio analysis (SWARA) method," *Environ. Sci. Pollut. Res.*, vol. 30, no. 11, pp. 31 851–31 880, 2023. https://doi.org/10.1007/s11356-022-24425-3

[47] A. Taibou, H. Jounaid, J. Moustadraf, and F. Amraoui, "Assessment of groundwater potential in the Khenifra-Azrou basin, Central Massif, Morocco using frequency ratio and Shannon'sentropy approaches," *Sci. Afr.*, vol. 27, p. e02616, 2025. https://doi.org/10.1016/j.sciaf.2025.e02616

[48] K. Gupta, S. Roy, R. C. Poonia, R. Kumar, S. R. Nayak, A. Altameem, and A. K. J. Saudagar, "Multi-criteria usability evaluation of mHealth applications on type 2 diabetes mellitus using two hybrid MCDM models: CODAS-FAHP and MOORA-FAHP," *Appl. Sci.*, vol. 12, no. 9, p. 4156, 2022. https://doi.org/10.3390/app12094156

[49] P. R. Jelenkovic, P. Momcilovic, and M. S. Squillante, "Scalability of wireless networks," *IEEE/ACM Trans. Netw.*, vol. 15, no. 2, pp. 295–308, 2007. https://doi.org/10.1109/TNET.2007.892846

[50] S. V. Dhage, A. N. Thakare, and S. W. Mohod, "An improved method for scalability issue in wireless sensor networks," in *2015 International Conference on Innovations in Information, Embedded and Communication Systems (ICIIECS)*, Coimbatore, India, 2015. https://doi.org/10.1109/ICIIECS.2015.7193264

[51] F. E. Mahmood, E. Perrins, and L. Liu, "Energy-efficient wireless communications: From energy modeling to performance evaluation," *IEEE Trans. Veh. Technol.*, vol. 68, no. 8, pp. 7643–7654, 2019. https://doi.org/10.1109/TVT.2019.2921304

[52] Y. Zhang and J. Li, "Study on spectrum allocation and optimization of wireless communication networks based on SFOA," *Wirel. Commun. Mob. Comput.*, vol. 2021, no. 1, p. 2262963, 2021. https://doi.org/10.1155/2021/2262963

[53] R. Koteeshwari and B. Malarkodi, "Spectrum sensing techniques for 5g wireless networks: Mini review," *Sens. Int.*, vol. 3, p. 100188, 2022. https://doi.org/10.1016/j.sintl.2022.100188

[54] M. A. S. Sejan, M. H. Rahman, M. A. Aziz, R. Tabassum, Y.-H. You, D.-D. Hwang, and H.-K. Song, "Interference management for a wireless communication network using a recurrent neural network approach," *Mathematics*, vol. 12, no. 11, p. 1755, 2024. https://doi.org/10.3390/math12111755

[55] Z. Ma, Y. Xiao, H. V. Poor, B. Vucetic, and M. Xiao, "High-reliability and low-latency wireless communication for internet of things: Challenges, fundamentals and enabling technologies," *IEEE Internet Things J.*, vol. 6, no. 5, pp. 7946–7970, 2019. https://doi.org/10.1109/JIOT.2019.2907245

[56] O. Babatunde, "The emerging technologies, use cases, prospects, and challenges of 6g wireless systems," *Int. J. Nov. Res. Dev.*, vol. 10, no. 1, 2025.

[57] J. F. de Morais and G. Siqueira, "Wireless technologies environmental impacts," in *2009 SBMO/IEEE MTT-S International Microwave and Optoelectronics Conference (IMOC)*, Belem, Brazil, 2009, pp. 523–527. https://doi.org/10.1109/IMOC.2009.5427529