Selection of Wireless Communication Technologies for Embedded Devices using Multi-criteria Approach and Expert Opinion

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ABSTRACT: Emerging research has shown the significance of communication technologies in the development of embedded systems and devices. Since there are various communication technologies with varying advantages and disadvantages in embedded systems, decision makers in identifying the best alternative can be prejudiced by various features. Hence, making the selection of the most suitable wireless communication technology a multi-criteria problem. To rank the common wireless communication technologies relevant to the development of embedded systems, this paper presents a multi-criteria decision making (MCDM) approach for analyzing experts opinion on the most preferred wireless communication technologies for embedded devices. To accommodate the subjective nature of experts' responses, a Fuzzy-TOPSIS MCDM approach is proposed for the ranking wireless communication technologies that can be adopted in the development of embedded systems. Based on the aggregation of responses from experts, the results show that the most preferred wireless communication alternative for embedded application is Wi-Fi with a closeness coefficient (CC_i) of 0.52, while the least preferred alternative is Long-Term Evolution (LTE) with a (CC_i) 0.32.

KEYWORDS: Wireless communication, Embedded systems, Internet of Things, Long-Term Evolution, Fuzzy-TOPSIS

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I. INTRODUCTION

The penetration of communication technologies (wireless and wired) in the design of embedded systems has helped the concept of smart devices and Internet-of-Things to take significant dives towards a practically achievable level. The idea of embedded systems which appeared long ago, begin to take concrete shape when key breakthroughs in various areas of life begin to take advantage of wireless communication technologies through home appliances, power and electronic equipment to mention a few. Today virtually all areas of life including agriculture, education, textile, health and energy are moving towards fulfilling the sustainable development goals, through the use of smart devices driven by embedded system enhanced tools and technologies (Adetunji, *et al*, 2022). A very fast developing and exciting technological area is the communication field. Wireless communication has to do with the transmission of data and information from one point to another without using any physical medium such as cables and wires (Teja and Mishra, 2021). In general, information transfer from a transmitter to a receiver over a limited distance defines a communication system. Between few meters, transmitter and receiver can be positioned anywhere just like the remote control of a television set or a few thousands of miles Satellite Communication.

Wireless communication has been in existence for decades just as embedded devices, the inclusion of the former in the functions of the later has enabled bi-directional and interoperable communication. Significant features such as energy optimization and efficiency, security, automation and integration of smart and intelligent devices delivered to end-users are being driven by wireless technologies. This ultimately results in making the world a better place through various applications. This work deals with the challenges of selecting the best wireless technology to be used for superlative delivery of embedded devices through practical realities. The progression in the wired and wireless communication and convenience of cheap embedded devices have resulted in expansion of many areas of application even remotely for internet of things in central heating systems. This includes Global Positioning Systems (GPS), domestic appliances (dish washers, televisions, digital phones and accessories, digital watches), electronic calculators, fitness trackers and engine management system in vehicles. Existing appliances are based on independent functions with limited remote, interoperable and smart features unlike embedded components which support wide range of applications in automation and excellent security features.

Wired communication media are more reliable in many applications when compared to wireless communications. However, wireless communication is becoming more popular due to mobility, ease of deployment, and occasionally; reduced cost of deployment (Teja & Mishra, 2021). When wireless

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technologies are being proposed for embedded systems, engineers are usually faced with the choice of the most preferred alternative because each of the available wireless communication technologies has its strength and weaknesses. Asides their technical strength and weaknesses, various features related to economic and ease of use are some of the things that engineers consider when making their choices. From the foregoing, it is evident that engineers are faced with conflicting criteria in their choice of wireless communication systems for embedded systems; this kind of scenarios creates what is known as a multi-criteria decision making problem. The central focus of this paper is to provide a framework that engineers and other stakeholders can use in selecting the most prefered wireless communication technologies based on more than one criterion to implement an excellent embedded device design. Some of the technologies reviewed in this work are Bluetooth, Long-Term Evolution (LTE), Z-wave, Classic WaveLAN, Wi-Fi and Zigbee. The selection of these technologies is based on their relevance and criteria for embedded device design such as Transmission Speed (TS), Security, Transmission Range (TR), Power Usage (PU), Development Cost (DC) and Development Complexity (DCOP). The Multi-criteria method used in the selection of wireless communication technologies coupled with illustrative examples, and future work are extensively discussed in this paper.

II. BRIEF OVERVIEW OF WIRELESS COMMUNICATION TECHNOLOGIES

The widespread of wireless communication and embedded system is becoming popular. Wireless communication network serves several purposes ranging from internet surfing on mobile devices and personal computers, general purpose handheld devices at considerably affordable prices depending on various part of the world (Gäwerth, 2017). In addition, one of the major merits of wireless network is the ability to connect and integrate a lot of services at reasonable prices (Silva-Pedroza *et al*, 2017). Various researchers have worked in similar areas of wireless technologies and embedded devices. The purppose of selecting the most appropriate communication technology involved in the design of embedded devices may be subjected to numerous criteria. This is a complex decision making especially in terms of TS, Security, TR, PU, DC and DCOP of the technology involved (Gore and Valsan, 2018). This purpose is germane to embedded device engineers, programmers and developers in making the right and well-informed decision through comparative analysis of various technologies rather than making a choice without taking cognizance of various criteria that may contribute positively to the device under consideration (Adebisi and Abdulsalam, 2021). This is a great improvement for making different choices that will be of a great advantage not only at the design and development stages but also will bring about continuous growth of output products, resolved compatibility issues, ease of repairs and maintenance, upgrading when required, improved security, and scaling up of developed embedded devices. Making a wrong choice in the technology used in driving embedded devices may be disastrous.

Ghamari *et al*., (2015) worked on Micro-Electro-Mechanical Systems (MEMS) and wireless communications in embedded solutions. Embedded devices monitoring health such as Body Area Network (BAN) implanted in the body was captured to measure vibrant parameters (blood pressure, heart rate, glucose levels). Data transfer of all the parameters were driven by wireless communication. The authors showed that the choice of wireless communication comes with various criteria such as energy consumption during data transmission. The work associated current and evolving minimum-power communication protocols that can be used for the deployment of BAN. Similarly, in (Usman & Shami, 2013), major communication technologies including Institute of Electrical and Electronics Engineers (IEEE) specified Local Area Network-LAN (Wi-Fi), WiMAX, The Global System for Mobile Communications (GSM) 3G/4G cellular, Power Line Communications (PLC) and Zigbee were discussed, although with no emphasis on choice and best selection.

However, these communications technologies focused on the application to smart grids realization for the assistance of modern advancement. It emphasized on the usage of wireless and wired technologies in embedded device driven technologies such as metering, home area, substation, infrastructure automation among others. Some of the challenges presented in the work of (Usman & Shami, 2013), is the selection of most suitable communication technology to justify the numerous opportunities in identified smart grid technologies. Kos *et al*., (2019), carried out a study on the applications of internet of things, sensors, wireless networks and wearable devices in a biofeedback solution specifically for sports. The biofeedback influences the implementation of routine in a person using feedback information. Various wireless technologies (actuators and sensors) were described by the authors as commonly used in the design of embedded devices related to sport. Most important constraints in the selection of relevant technologies were also raised and presented through essential architectures of a typical biofeedback system. The work considered illustrative examples with specific scenarios in sport matching suitable and scalable wireless technologies that could grant increased data rates in a long time. The result of the work revealed that the identified wireless technologies do not satisfy the demands of biofeedback solutions based on the scenarios.

Research such as intelligent transport system and modeling analysis for heart attack (life-threatening cardiac diseases) embedded devices were also reviewed (Dar *et al*., 2010). The authors explored available wireless communication technologies and their capabilities for future applications with emphasis on the best presented communication interface for the target solutions. The peculiarity of embedded electrocardiogram (ECG) devices requires resourceful algorithms driven by minimal energy consumption, continuous monitoring of signals for practical usage. Kim *et al*., (2021) and Ma *et al*., (2015) examined three possible models of transmitting data for energy consumption in a simulated environment and its computational efficiency recorded up to 84.67% per 508 s of data segment. The application of wireless communications and sensors in ecommerce, security and healthcare coupled with distinctive characteristics are often faced with many challenges regarding choice. In addition, Lin *et al*., (2004), identified limited supply of energy, rate of data transmission, innovative design methodologies and some operating characteristics are some of the rigorous desires in the selection of wireless technologies used for embedded devices design and packaging.

From the review, the challenges of making the right choice in the selection of the most preferred wireless communication technology for the design of embedded system solution has existed for long. In the recent times, wrong selection of wireless technology may lead to reduced Quality of Service (Qos) in the deployment of sensitive applications such as robotic and critical control Systems (Calvo *et al*., 2021). The proposed multi-criteria selection methodology in this work will assist better understanding of wireless technology choice based on key criteria with the consideration of specified rules especially when it comes to real life solutions as emphasized in Kavnuch *et al*., (2020)

The fast and rapid rate at which technological innovations are moving requires the right choice of communication technologies. Most tools share similar features with their respective effects and conduct on the purpose of usage. Despite the evolution of new technologies, the old ones are still very much around, not substituted but make provision for supplementary choices and improved functionalities. Although, new communication technology poses some level of competition to the existing tools based on product designer choices and criteria. There are several wireless communication technologies (General Packet Radio Services (GPRS), Edge, 3G, 4G) which are widely deployed in embedded sensor devices across sports, ecommerce, health, agriculture, and education as suitable for real-time purposes. The following popular wireless technologies were explored in this research for the best selection based on required criteria.

A. Bluetooth

This is a wireless communication technology (packet-based protocol) used for short distance communication. They are popularly deployed in Personal Area Networks (PAN). It is a standard IEEE 802.15.1 and it is commonly found in mobile devices and headsets, with the operation range of 2.4 GHz allowable for data exchange within 100 m. It enables data transmission in a strong manner using a frequency-hopping spread spectrum. Bluetooth uses the same hopping arrangement in the assignment of address spaces. With the presence of profile and core specification, it manages required functions to acclimatize new technology and applications. The interpretation of individual Bluetooth profile is very germane to the usage of Bluetooth wireless technology. Certain behaviour needs to be enabled for devices to communicate through settings and parameters. Many different applications described different cases of Bluetooth profiles. This technology is largely compactible, simple and one of the most common wireless technologies.

B. LTE

Sometimes referred to as fourth generation Long Term Evolution (4G LTE). Allows data transmission and download of contents especially media in very fast and standard mode than previous technologies. It is specifically designed to increase speed capacity on mobile networks (Figure 1). Extremely characterized with very high performance for cellular communication devices, LTE comes at relatively reduced cost, offers flexibility, simplified architecture, and realistic power consumption with more services. The incorporation of Orthogonal Frequency Division Multiplex (OFDM) into LTE strengthens the bandwidth to be conveyed proficiently. Most of the main challenges of previous technologies which arose from multiple signals are addressed in LTE. It essentially provides increased throughput coupled with very high resilience to reflections and interference while routing data directly to its destination.

C. Z-wave

This is a wireless communication technology that supports interoperability especially at the application layer of the OSI model. Since embedded devices share information between hardware and software, the place of z-wave cannot be over emphasized in allowing hardware to interoperate with software. It has the capability of achieving data rate of 40 and 100 kbit/s providing cloud access through gateway (Z-wave bridge). They are embedded device protocols that are implemented on chips with frequency specification of sub-1 GHz band between 865 to 926 MHz routed through network architecture while the physical range covers up to 100 m. It functions more within low-power Radio Frequency Identification (RFID) communication with a reasonable support for home automation.

D. Classic WaveLAN

This is a wireless communication technology that uses 64-bit and 128-bit data encryption technology. It is used in different families of wireless communication, it was a proprietary protocol before the advent of 802.11. It is one of the technologies that led to the creation of Wi-Fi, and it is established with a goal to provide more security and confidentiality when compared to wired technologies. The first application was named Wired Equivalent Privacy (WEP). It is well matched with other monitoring and communication management wireless technologies, it is good for domestic and commercial areas. The major advantage is the provision of reliable transmission for not too long messages from one unit to other nodes on the network. It gives room for full-type topology without a coordinator (Krapivina *et al*., 2019).

E. Wifi

This is a technology that translates radio signals from wireless router to devices that are not too far from each other into meaningful data. It is simply an internet connection medium shared with many devices within a home or commercial areas. Wi-Fi enabled devices receive internet connections directly from router or MODEM during broadcast. As long as users are within the network range, Wi-Fi gives network constant connectivity known as IEEE 802.11 which uses radio waves for transmission. The application can be found in various devices (embedded and non-embedded) such as smartphone and other mobile devices, computers, televisions among others. Since communication occurs over airwaves, the devices and other information can be at security

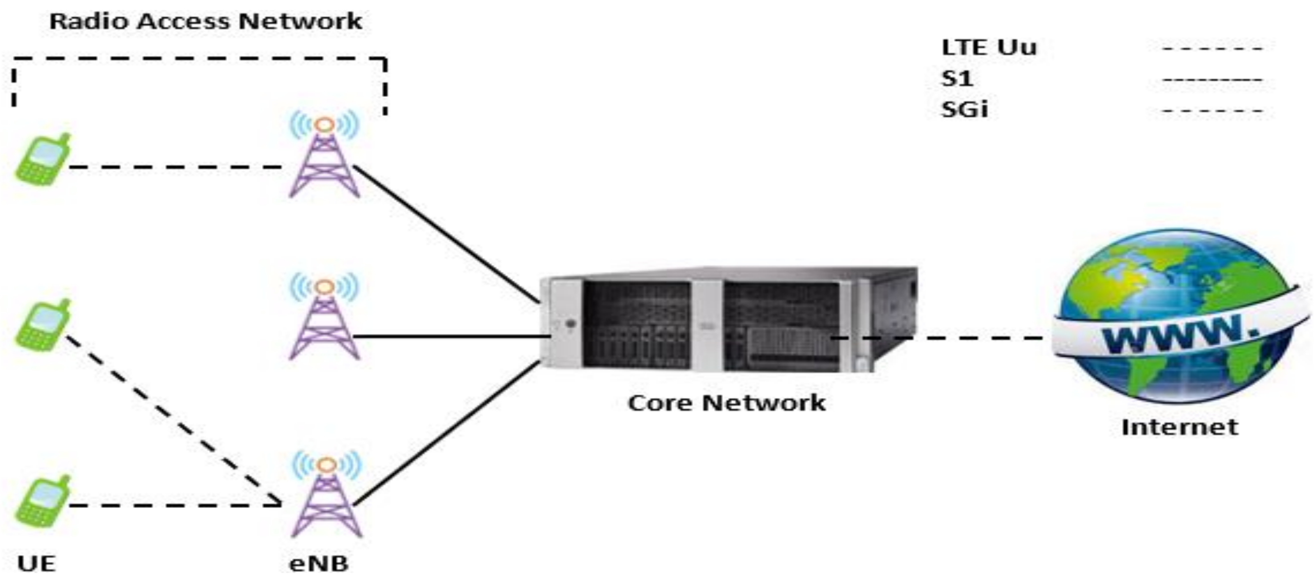

Figure 1: LTE Network Diagram Source: Adapted from (Stiller *et al*., 2020).

risk, exposed to hackers (cyber-attacks) among other threats. This become very challenging when using devices with free or public channels that are not password protected. Implemented with a security feature, Wi-Fi performances are very good in collective spectrum and noisy RF channel atmosphere. In Wi-Fi communication technology, IP based protocols are used (point-to-point and point-to-multipoint). Table 1 provides a summary of the wireless communication technology alternatives and their additional features.

Table 1: Standardized wireless technologies with details.

Technology	Frequency	Range	Bit rate	TX Power
Bluetooth	2.4GHz	10-100m	1-3Mbits/s	2.5-100mW
Zigbee	867MHz and 2.4GHz	10-100m	20-250kbits/s	1-100mW
Wifi	2.4GHz	70m	600Mbits/s	100mW
Classic WaveLAN	2.4GHz	45	600Mbits/s	32mW
Z-wave	800-900MHz	100m	100kbits/s	1mW
LTE	20MHz	1732m	299.6Mbits/s	200mW

Criteria Used in this study
Transmission Speed ($\boldsymbol{C_1}$), Security ($\boldsymbol{C_2}$), Transmission Range ($\boldsymbol{C_3}$), Power Usage ($\boldsymbol{C_4}$), Development Cost ($\boldsymbol{C_5}$), and Development Complexity ($\boldsymbol{C_6}$)

F. *Zigbee*

Zigbee is a wireless communication technology with applications in monitoring and control of various equipment. It has the capacity to monitor online parameters working with different factors with absolute security. Its strong authentication process (128-bit AES Encryption) between communicating devices is amazing. In addition to embedded devices and consumer electronics; other usage of Zigbee found its place in healthcare, building automation, energy management and efficiency, industrial control and telecommunication services. Most often Zigbee appears as a choice when it comes to Home Area Network (HAN) at the domestic level. It is a platform for communication with low power consumption though within a little range/small data rate. The communication technology can connect up to two hundred and fifty-four devices. It is flexible, scalable and maintainable.

III. METHODOLOGY

The methodology developed to implement the aim of this research is presented in this section. Shown in Figure 2 is the proposed framework for the selection of wireless communication technologies for embedded devices. This proposed framework deploys the distinctive features of Fuzzy-TOPSIS techniques. The aggregation method was used to evaluate the significance/weight of evaluation criteria based on expert opinion. Ranks for the wireless communication technologies are calculated using the fuzzy-TOPSIS method. In the proposed framework, experts' viewpoints generate the information used for the proposed model appraisal.

A. *Fuzzy TOPSIS*

TOPSIS Multiple-criteria Decision Making (MCDM) approach is based on the ideology that the most suitable or best alternative must have the shortest distance to Positive Ideal Solution (PIS) while the least preferred alternative usually have the farthest distance to Negative Ideal Solution (NIS). As an extension of the TOPSIS method, Chen, (2000) implemented a vertex approach to estimate the distance between two triangular fuzzy numbers as defined in Eqn. (1).

$$d(\tilde{x},\tilde{y}) \coloneqq \sqrt{\frac{1}{3}[(a_1-a_2)^2+(b_1-b_2)^2+(c_1-c_2)^2]} \quad (1)$$

$\tilde{x}=(a_1,b_1,c_1), \tilde{y}=(a_2,b_2,c_2)$ is specified as two triangular fuzzy numbers.

According to Chen (2000) The procedures in the realization of the Fuzzy-TOPSIS technique includes:

Step 1: Allocate ratings to the relationship between the alternatives and their criteria. Suppose opinion is taken from P

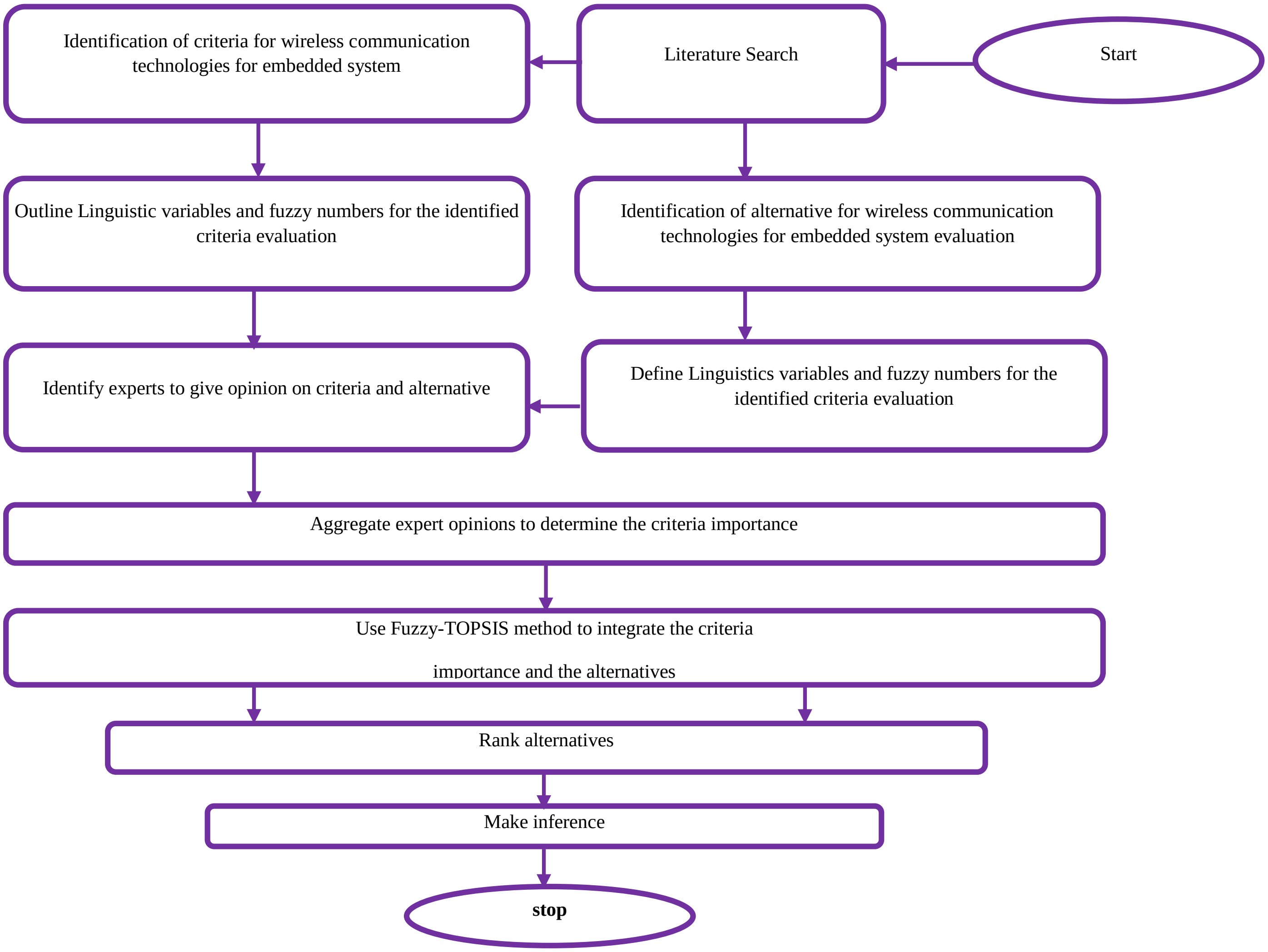

Figure 2: Proposed framework for the selection of wireless communication technologies for embedded devices

number of professionals, then the fuzzy rating of the P^{th} professional on an alternative A_i with regards to criterion C_j is given as $\tilde{x}_{ij}^p = (a_{ij}^p, b_{ij}^p, c_{ij}^p)$, while the importance attached to the criterion C_j is given as $\tilde{w}_j^p = (w_{j1}^p, w_{j2}^p, w_{j3}^p)$.

Step 2: Evaluate the fuzzy weights for the criteria and the combined fuzzy scores for the alternatives. To compute the aggregate of the fuzzy score $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij})$ of the i^{th}alternative in relation to j^{th}criterion Eqn.6 is used:

$$a_{ij} = \min_p\{a_{ij}^p\},\ \ b_{ij} = \frac{1}{p}\sum_{p=1}^{p} b_{ij}^p,\ c_{ij} = \max_p\{c_{ij}^p\} \tag{2}$$

Also, the aggregate of the fuzzy weight $\tilde{w}_{ij} = (w_{j1}, w_{j1}, w_{j3})$ of the criterion C_j is calculated as:

$$w_{j1} = \min_p\{w_{j1}^p\},\ \ w_{j2} = \frac{1}{p}\sum_{p=1}^{p} w_{j2}^p,\ w_{j3} = \max_p\{w_{j3}^p\} \tag{3}$$

Step 3: calculate the normalized fuzzy decision matrix. The normalized fuzzy decision matrix is given as:

$$\tilde{R} = [\tilde{r}_{ij}] \tag{4}$$

But,

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right) \text{ and } c_j^* = \max_i\{c_{ij}\} \text{ (beneficial)} \tag{5}$$

$$\tilde{r}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right) \text{ and } a_j^- = \min_i\{a_{ij}\} \text{ (cost)} \tag{6}$$

Step 4: determine the weight of the normalized decision matrix $\tilde{V}$:

$$\tilde{V} = (\tilde{v}_{ij});\ \tilde{v}_{ij} = \tilde{r}_{ij} \times w_j \tag{7}$$

Step 5: calculate the fuzzy PIS (Eqn.8) and Fuzzy NIS (Eqn.9):

$$A^* = (\tilde{v}_1^*, \tilde{v}_2^*, \ldots \tilde{v}_n^*), \text{ where } \tilde{v}_j^* = \max_i\{v_{ij3}\}; \tag{8}$$

$$A^- = (\tilde{v}_1^-, \tilde{v}_2^-, \ldots \tilde{v}_n^-), \text{ where } \tilde{v}_j^- = \min_i\{v_{ij1}\}; \tag{9}$$

Step 6: Calculate the distance from each alternative to the fuzzy PIS and fuzzy NIS: Eqns. 10(a and b) is used to obtain the distance from each alternative A_i to the fuzzy PIS (Eqn. 10a) and to the fuzzy NIS (Eqn. 10b).

$$d_i^* = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^*), \tag{10a}$$

$$d_i^- = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^-), \tag{10b}$$

Step 7: Evaluate the closeness coefficient for each alternative using Eqn. 11

$$CC_i = \frac{d_i^-}{d_i^- + d_i^*} \tag{11}$$

Step 8: The alternative with highest value of closeness coefficient is the most suitable alternative, while the alternative with the smallest value of closeness coefficient is the least preferred.

IV. RESULTS AND DISCUSSION

An illustrative example of selecting a wireless technology for embedded application is presented in this section. The Fuzzy-TOPSIS method was implemented by ranking 6 alternatives based on six criteria. The alternative includes Bluetooth (W_1), LTE (W_2), Z-wave (W_3), Classic WaveLAN (W_4), Wifi (W_5), and Zigbee (W_6).

The criteria considered are Transmission Speed (C_1), Security (C_2), Transmission Range (C_3), Power Usage (C_4), Development Cost (C_5), and Development Complexity (C_6). Using the 10-point linguistic term presented in Figure 3, the expert were consulted to rank the relationship between the identified technologies and the selected criteria.

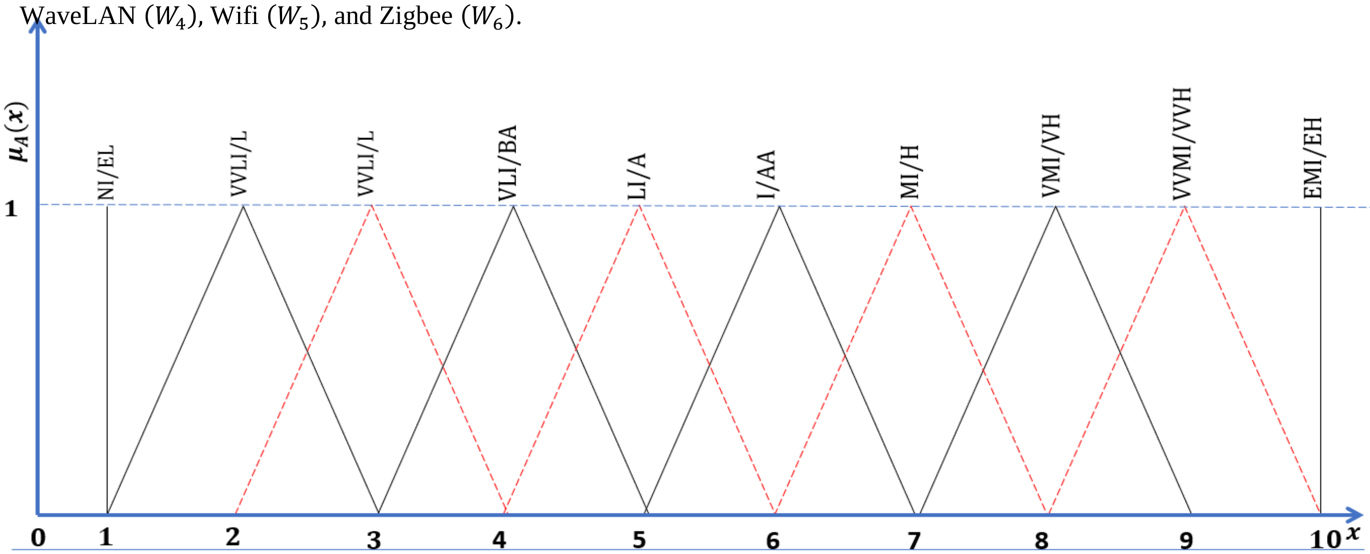

Figure 3: Ten-point fuzzy scale adopted in this study.

Legend
Not Important/Extremely Low -NI/EL — Very Very Less Important/ Low - VVLI/L
Very Very Less Important/ Low -VVLI/L — Very Less Important/ Below Average - VLI/BA
Less Important/ Average -LI/A — Important/Above Average - I/AA
More Important/ High - MI/H — Very More Important/Very High-VMI/VH
Very Very More Important/ Very Very High - VVMI/VVH
Extremely More Important/ Extremely High - EMI/EH

Table 2: Expert opinion on wireless technologies for embedded systems.

P1

	C_1	C_2	C_3	C_4	C_5	C_6
W_1	VVH	AA	VH	L	A	VH
W_2	L	EH	VH	A	H	H
W_3	H	H	AA	VL	A	H
W_4	VH	H	VH	A	H	AA
W_5	H	H	H	A	A	AA
W_6	VH	H	H	AA	AA	AA

P2

	C_1	C_2	C_3	C_4	C_5	C_6
W_1	VVH	EH	VH	EH	VVH	EH
W_2	H	H	VVH	VVH	VVH	EH
W_3	AA	H	EH	VVH	VVH	VVH
W_4	EH	VH	H	VH	AA	VH
W_5	VH	VVH	EH	EH	VH	VVH
W_6	H	H	VVH	AA	H	H

P3

	C_1	C_2	C_3	C_4	C_5	C_6
W_1	H	H	VH	H	A	VH
W_2	H	VH	VH	H	A	VH
W_3	EH	AA	L	BA	VH	AA
W_4	H	AA	H	H	AA	VH
W_5	H	EH	AA	H	AA	VVH
W_6	H	H	AA	H	AA	H

P4

	C_1	C_2	C_3	C_4	C_5	C_6
W_1	VH	AA	High	VH	H	VH
W_2	VVH	AA	VVH	VH	VH	VH
W_3	A	AA	A	A	A	A
W_4	EH	VH	EH	EH	EH	EH
W_5	VH	VH	VH	VH	VH	VH
W_6	H	H	H	H	H	H

P5

	C_1	C_2	C_3	C_4	C_5	C_6
W_1	VVH	AA	VVH	VH	H	VH
W_2	VH	VH	VH	VH	VH	VH
W_3	VH	VVH	VH	VVH	VH	VVH
W_4	VH	H	VH	VH	VH	VH
W_5	H	VVH	VH	VH	VH	VH
W_6	VVH	VH	VH	VH	VH	VH

The relationship between the alternatives and criteria is used to form the intuitionistic fuzzy decision matrix (Mahase *et al*., 2016). A total of five experts (P1-P5) in the area of wireless technologies were selected from both the industry and the academia to give their professional opinion on the subject. This was done through the use of a well-structured questionnaire where experts were encouraged to evaluate alternative solutions according to the indicated criteria using the 10-point rating scale. The 10-point fuzzy rating scale was adopted so has to accommodate the fuzzy nature of the responses that would be supplied by the experts.

With each expert allocated the same weight, the responses of the five experts with respect to the wireless network alternatives are given in Table 2. The responses of the experts were presented in linguistic terms and then converted to triangular intuitionistic fuzzy numbers. Basic fuzzy number operators were used to combine the responses of the experts on the relationship between the alternatives and the criteria and their opinion on the proper weights that should be allocated to the criteria.

The results of the aggregated opinion of the experts with respect to the technologies are presented in Table 3 while the aggregated responses on the weights of the criteria are presented in Table 4. To obtain the weighted normarlized decision matrix (Table 5), the results of the combined decision matrix is used to multiply (using the fuzzy operator) aggregated responses on the weights of the criteria.

To obtain the distance from each alternative to the fuzzy PIS and fuzzy NIS Eqns. 1 and 8-1 are combined and deployed. The result of this step is presented in Table 6. Furthermore, the closeness coefficient for each alternative is calculated and used in the ranking of the wireless alternatives. From Table 7, based on the experts' opinion, the most preferred wireless technology for embedded system application is the Wifi becuase; it has the highest closeness coefficient. The next most preferred wireless technology is the Z-wave with a closeness index of 0.5, followed by Bluetooth, classic Wave, LAN, and Zigbee respectively. The least preferred wireless technology for embedded system is the LTE with a closeness index of 0.26.

V. CONCLUSION

This article presented an evaluation of some of the existing wireless communication technologies that could possibly be used in the development, application and usage of embedded devices. From previous studies, various wireless communication technologies have been ranked based on different criteria using expert opinions and multi-criteria decision-making analysis. In the development of embedded devices, different stakeholders have diverse objectives to be met which may be translated into criteria in obtaining the most preferred wireless communication technologies (alternatives). In this study, a total of 6 wireless communication technologies (Bluetooth (W_1), LTE (W_2), Z-wave (W_3), Classic WaveLAN (W_4), Wifi (W_5), and Zigbee (W_6)) were identified from the literature and ranked based on 6 criteria which included

Table 3: Combined results of expert opinion.

	C$_1$	**C$_2$**	**C$_3$**	**C$_4$**	**C$_5$**	**C$_6$**
W$_1$	(4,6,9)	(4,6,10)	(1,3.6,8)	(2,5,8)	(1,4.8,8)	(1,6.6,10)
W$_2$	(5,7.8,are)	(6,8,10)	(2,8,10)	(6,8.6,10)	(4,7.4,10)	(5,8.2,10)
W$_3$	(4,6.8,10)	(5,7.4,10)	(4,6.8,9)	(1,6,10)	(3,6,9)	(6,8,10)
W$_4$	(2,7.4,10)	(3,7,10)	(4,7.2,9)	(1,6.6,10)	(5,7,10)	(4,7,10)
W$_5$	(7,8.8,10)	(6,8.6,10)	(6,8,10)	(2,7,10)	(2,6.6,10)	(3,7.2,10)
W$_6$	(4,6.8,9)	(5,7.2,10)	(2,5.4,10)	(3,5.6,10)	(2,5,8)	(2,5.6,8)

Table 4: Combined weights of criteria.

Criteria	**Importance of criteria**					**Combined weight**
	P1	P2	P3	P4	P5	
C$_1$	VVMI	MI	I	MI	VMI	(5,8,10)
C$_2$	EMI	VVMI	I	EMI	VMI	(5,8.8,10)
C$_3$	VMI	EMI	I	VMI	VMI	(7,9.2,10)
C$_4$	VMI	EMI	VVMI	I	MI	(6,8.8,10)
C$_5$	VVMI	VMI	EMI	I	VMI	(4,7,10)
C$_6$	MI	VVMI	EMI	VMI	VMI	(4,6.2,8)

Table 5: weighted normalized fuzzy decision matrix.

	C$_1$	**C$_2$**	**C$_3$**	**C$_4$**	**C$_5$**	**C$_6$**
W$_1$	(2.00, 4.80, 9.00)	(2.00, 5.28, 10.00)	(0.70, 3.31, 8.00)	(0.75, 1.76, 5.00)	(0.50, 1.46, 10.00)	(0.40, 0.61, 8.00)
W$_2$	(2.50, 6.24, 10.00)	(3.00, 7.04, 10.00)	(1.40, 7.36, 10.00)	(0.60, 1.02, 1.67)	(0.40, 0.95, 2.50)	(0.40, 0.49, 1.60)
W$_3$	(2.00, 5.44, 10.00)	(2.50, 6.51, 10.00)	(2.80, 6.26, 10.00)	(0.60, 1.47, 10.00)	(0.44, 1.17, 3.33)	(0.40, 0.50, 1.33)
W$_4$	(1.00, 5.92, 10.00)	(1.50, 6.16, 10.00)	(2.80, 6.62, 9.00)	(0.60, 1.33, 10.00)	(0.40, 1.00, 2.00)	(0.40, 0.57, 2.00)
W$_5$	(3.50, 7.04, 10.00)	(3.00, 7.57, 10.00)	(4.20, 7.36, 10.00)	(0.60, 1.26, 5.00)	(0.40, 1.06, 5.00)	(0.40, 0.56, 2.67)
W$_6$	(2.00, 5.44, 9.00)	(2.50, 6.34, 10.00)	(1.40, 4.97, 10.00)	(0.60, 1.57, 3.33)	(0.50, 1.40, 5.00)	(0.50, 0.71, 4.00)
A*	(3.50, 7.04, 10.00)	(3.00, 7.57, 10.00)	(4.20, 7.36, 10.00)	(0.75, 1.76, 10.00)	(0.50, 1.46, 10.00)	(0.50, 0.71, 8.00)
A-	(1.00, 4.80, 9.00)	(1.50, 5.28, 10.00)	(0.70, 3.31, 8.00)	(0.60, 1.02, 1.67)	(0.40, 0.95, 2.00)	(0.40, 0.49, 1.33)

Tabe 6: Distance from each alternative to the FPIS and FNIS.

Distance from FPIS

	C_1	C_2	C_3	C_4	C_5	C_6
W_1	1.66	1.44	3.30	2.89	0.00	6.08
W_2	0.74	0.30	1.62	4.83	4.34	4.42
W_3	1.27	0.67	1.18	0.19	3.85	4.40
W_4	1.58	1.19	1.08	0.26	4.63	4.45
W_5	0.00	0.00	0.00	2.90	2.90	4.53
W_6	1.39	0.77	2.13	3.85	2.89	4.73

Distance from FNIS

	C_1	C_2	C_3	C_4	C_5	C6
W_1	0.58	0.29	0.00	1.97	4.63	3.85
W_2	1.33	1.34	2.64	0.00	0.29	0.15
W_3	0.90	0.92	2.17	4.82	0.78	0.01
W_4	0.87	0.51	2.34	4.81	0.03	0.39
W_5	2.02	1.58	3.30	1.93	1.73	0.77
W_6	0.69	0.84	1.55	1.01	1.75	1.55

Table 7: Final ranking.

Alternative	d_i^*	d_i^-	CC_i	Rank
W_5	10.33	11.33	0.52	1
W_3	11.57	9.58	0.45	2
W_1	15.37	11.32	0.42	3
W_4	13.19	8.95	0.40	4
W_6	15.75	7.39	0.32	5
W_2	16.25	5.75	0.26	6

Transmission Speed (C_1), Security (C_2), Transmission Range (C_3), Power Usage (C_4), Development Cost (C_5), and Development Complexity (C_6). Each of the alternatives has strengths and weaknesses, hence necessitated this study to present discussion for the selection and ranking of the most prefered wireless communication alternative that can be used in the development of embedded devices. In this study, equal weights were allocated to the experts. Expert opinion on the identified wireless technologies and alternatives suggests that the most preferred wireless technology alternative for embedded system is Wi-Fi with highest value of closeness coefficient of 0.52 while the least preferred alternative is the LTE technology with the lowest value of closeness coefficient (0.32).

Further study that will present the ranking of the wireless communication technologies based enirely on the technical features on the user's manual and compare the results to that presented by experts' opinions is underway. This will include the comparative analysis of the application of other MCDM tools to the same subject.

AUTHOR CONTRIBUTIONS

J. A. Adebisi: Conceptualization, Software, Validation, Writing – original draft. **O. M. Babatunde:** Conceptualization, Methodology, Supervision. **J.A. Adebisi and O. M. Babatunde:** Writing – review & editing.

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