IEEE Access
Multidisciplinary ⁝ Rapid Review ⁝ Open Access Journal

Received March 11, 2019, accepted March 27, 2019, date of publication April 1, 2019, date of current version April 17, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2908764

Network Selection Algorithm for Multiservice Multimode Terminals in Heterogeneous Wireless Networks

HEWEI YU[1], YANAN MA[1], AND JINGXI YU[2]
[1]School of Computer Science and Engineering, South China University of Technology, Guangzhou 510640, China
[2]Department of Mathematics, University of Washington, Seattle, WA 98195, USA

Corresponding author: Yanan Ma (myn0429@163.com)

This work was supported in part by the Natural Science Foundation of Guangdong Province under Grant 2017A030307035, in part by the Innovative Research Project of the Education Department of Guangdong Province under Grant 2017KTSCX127, and in part by the Science and Technology Project of Yuexiu under Grant 2018-GX-013.

ABSTRACT The rapid popularization of multimode terminals that simultaneously run multiple services (such as browsing web pages during a video session) has brought a decent amount of attention to the network selection problem of multimode terminals. However, most network selection algorithms proposed for vertical handoff are only suitable for terminals running a single service. This paper proposes a network selection algorithm for multiservice multimode terminals in heterogeneous wireless networks. The algorithm considers user preferences, network attributes, and service characteristics. Entropy and fuzzy analytic hierarchy process (FAHP) are used to calculate the objective weights of the network attributes and the weights determined by the service characteristics, respectively. The comprehensive weights of network attributes are obtained by combining the user preferences and service priority. At the same time, different utility functions are used to calculate the utility values of the network attributes for multiservice. Finally, the simple additive weighting (SAW) method is used to synthesize the utility values and the comprehensives weights, while the most appropriate network is selected by a technique for order preference by similarity to an ideal solution (TOPSIS) and a threshold. The simulation results show that the proposed algorithm can accurately select the most appropriate network by considering different factors. Compared to the existing two MMT network selection algorithms, it can reduce the number of vertical handovers and obtain better user experience while satisfying user's preferences and service's requirements, thus solving the multiservice multimode terminals network selection problem.

INDEX TERMS FAHP, heterogeneous wireless networks, multiservice multimode terminals, TOPSIS.

I. INTRODUCTION

The popularity of Internet applications allows users to enjoy multiple services anytime and anywhere. However, a single network cannot meet the requirements of all services, so it is inevitable that heterogeneous wireless networks (HWNs), which overlap each other, appeared. Different radio access technologies (RATs) have different characteristics, which makes it important to choose the most appropriate network for multimode terminals (MTs). The purpose of a RAT selection algorithm is to select the most suitable RAT for incoming call(s) in a HWN [1], [2]. MTs for next generation wireless networks (NGWNs) have the capability to support two or more different classes of calls simultaneously [2]–[4]. While much research effort has concentrated on developing vertical handoff (VHO) decision algorithms for a single-session from an MT, not much has been reported in the literature on RAT selection for a group of handoff sessions from an MT in NGWNs [5].

Network selection is a major component of the VHO process, and MT must connect to the network in the optimal way according to the Always Best Connected (ABC) principles. When selecting access, a number of different aspects need to be considered. One is the ABC user profile, which contains the user's personal preferences for choice of access. Another is the network characteristics (e.g., available bandwidth, cost, and operator). Other aspects are device capabilities and application requirements [6]. At present, there are many researches on network selection algorithms in HWN. These algorithms can be divided into

The associate editor coordinating the review of this manuscript and approving it for publication was Prakasam Periasamy.

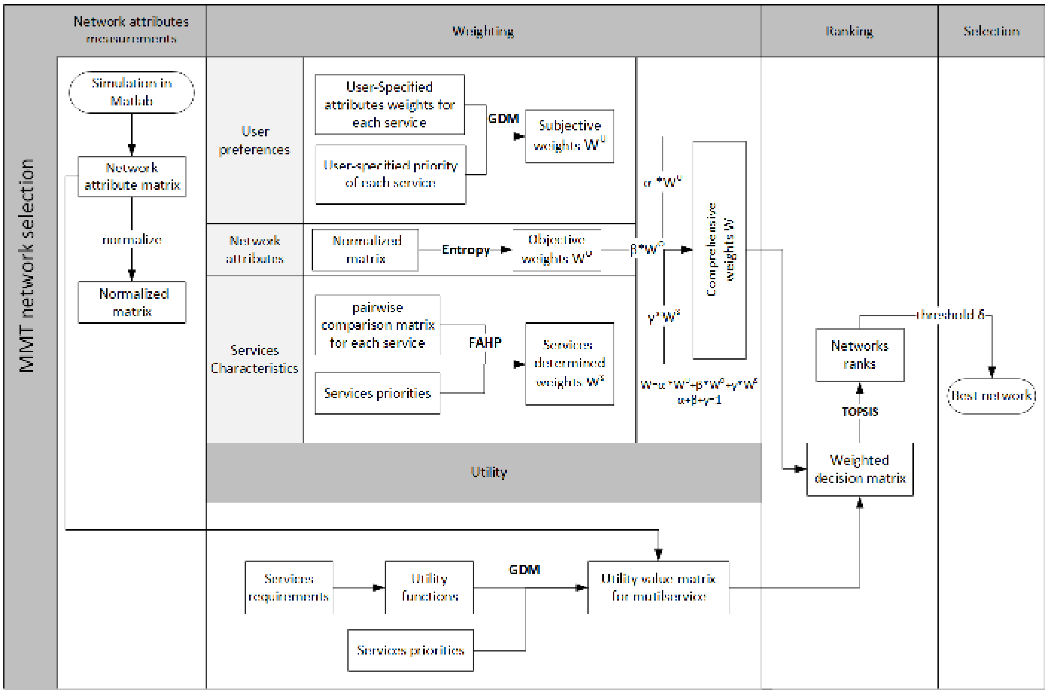


FIGURE 1. System architecture and algorithm model flowchart.

five categories [7]: cost function based algorithms [8], [9], user-centered algorithms [10], [11], fuzzy logic and neural network based algorithms [12], [13], multiattribute based algorithms and context-aware algorithms [14]. Multiattribute based algorithms also include Hierarchical Analysis Process (AHP) [15], Fuzzy Analytic Hierarchy Process (FAHP) [16], Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) [17], ELECTRE [18], Simple Additive Weighting (SAW) [19], Multiplicative Exponent Weighting (MEW) and so on. All the algorithms above only consider the network selection of a single call in the HWN, but have not considered the network selection problem when the MT is running multiple services at the same time.

The problem of network selection for multiservice multimode terminals (MMTs) is still a relatively new topic. The existing works in this field only considered the MMT network selection under a single factor, such as user preferences or service requirements. This causes an overly subjective or objective choice. There is no comprehensive MMT network selection algorithm to meet both user needs and application requirements. This does not match the use of MMT. In order to solve this problem, we propose a new MMT network selection algorithm that takes into consideration user preferences, service characteristics and requirements, and network attributes to select the best network for MMT among many available networks.

In this work, we use group decision making (GDM) technology to select the best network for MMT, which takes each service from a MMT as a decision maker. In the process of network selection, the requirements of all decision makers should be considered, and a network that maximizes the interests of the entire group should be selected. The system architecture is shown in Fig. 1. The algorithm selects the most appropriate network for MMT based on TOPSIS, Entropy, FAHP, utility function and other techniques. The weights of network attributes determined by each service's characteristics are calculated using FAHP, and the weights determined by all the services are calculated by combining with the services priorities using GDM. Entropy calculates the objective weights of the network attributes. The network attributes weights and service priority of each service specified by the user represent user's preferences, and GDM is used to obtain user-specified network attributes weights. We synthesize the weights of the three aspects above to obtain the comprehensive weights of network attributes. Then, according to the requirements of different services, use the utility functions to normalize the network attributes of each service, so as to obtain the comprehensive utility values of the network attributes for multiservice. After that, the decision matrix is constructed by SAW that synthesizes comprehensive weights and utility values. At last, use TOPSIS to calculate the scores of the networks, and the most appropriate network is finally selected based on the scores and a threshold. The main contributions of our algorithm are as follows:

a) We propose a comprehensive MMT network selection algorithm, which combines multiple factors successfully and obtains more satisfactory and stable network selection.
b) Consider user preferences, network attributes and service characteristics and requirements synthetically, not only avoiding users' judgments to be too subjective,

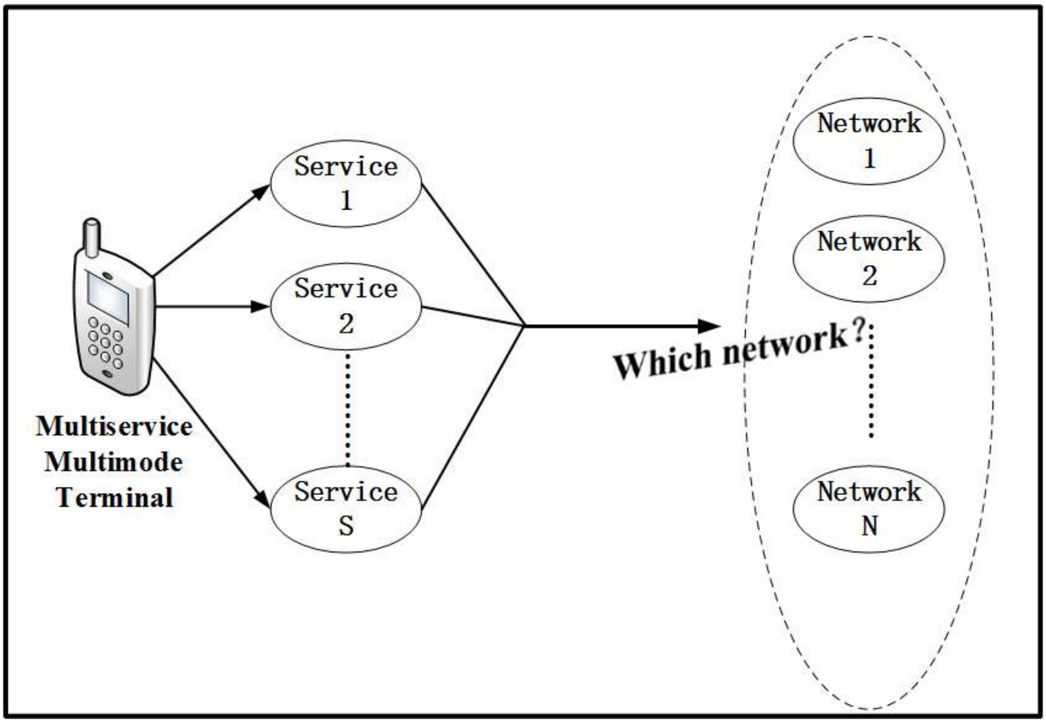


FIGURE 2. MMT network selection problem in HWN.

but also alleviating the services' selection to be too objective.

c) Use a threshold to avoid unnecessary handoff, thereby reducing the number of handoffs and avoiding unnecessary handovers to reduce ping-pong effect.

The rest of this paper is organized as follows: Section II introduces the related work of MMT network selection. Section III describes the proposed MMT network selection algorithm in detail. Simulation experiments and results analysis are shown in Section IV. Section V summarizes this paper and points out the shortcomings and future work.

II. RELATED WORK

Next generation MTs are equipped with multiple network interfaces that have the capability to support multiple services [5]. Due to terminal's power limitation, we haven't consider the problem that MMT can connect multiple networks at the same time. Therefore, the network selection problem of MMT is a GDM problem, as shown in Fig. 2. The MMT running multiple services at the same time selects the most appropriate network or handovers vertically from the current network to the optimal network. Only a few algorithms about the network selection problem of MMT in HWN have been proposed [1]–[5], [20]–[22].

Falowo and Chan [3] first studied the problem of making vertical handover decisions for multiple classes of services from a MMT in HWNs and proposed an algorithm. To reduce the frequency of vertical handover, Falowo and Chan [1] used a RAT preference margin which represents the metric of the target network superior to the current connected network and proposed a dynamic MMT RAT selection algorithm. In order to capture the dynamic and highly ambiguous nature of the heterogeneous wireless environment, Paul and Falowo [20] used Intuitionistic Fuzzy TOPSIS to develop a framework that selects the best network for different MMTs. Furthermore, for the sake of making a more appropriate choice between call-by-call decisions and group call decisions for multiple services in a HWN, Falowo and Taiwo [2] investigated independent call and group call RAT selection decisions for multiple services in HWNs, and proposed a multi-calls RAT selection scheme based on the consensus level among the multiple services. GDM is used when the level of consensus among multiple services allowed to access a particular RAT equal or greater than a certain threshold. Otherwise, the scheme will make independent decisions. However, only user preferences have been considered in [1]–[3], and [20].

Luo *et al.* [21] proposed a MMT network selection algorithm based on GDM in HWNs, which considers each service from the MMT as a decision-maker and obtain the synthesized weight vector of all network attributes for multiservice by AHP and GDM according to the service characteristics. Sigmoid utility function is used to normalize the network attributes, and the network selection is made according to the synthesis of weight vector and attribute utility. However, only service characteristics have been considered in this algorithm.

As for the study of dynamic factors of the MMT network selection, Falowo and Chan [4] developed an analytical model for calling dynamics of a MMT, to investigate the effect of call dynamics of RAT selection in HWN. What's more, in order to investigate the impact of dynamic criterion (i.e., terminal speed) and the degree of importance of class of call, Obayiuwa and Falowo [22] proposed a MULTIMEROA algorithm for group calls' network selection in HWN. However, these two just take user preferences into account.

In order to analyze the MMT network selection algorithms, Taiwo and Falowo [5] assessed the cross-analysis of four candidate algorithms, comparing SAW-GDM, MEW-GDM, TOPSIS-GDM and DIA-GDM four multi-criteria group decisions candidate algorithms. However, the weights are only specified by user for all algorithms.

From the reviewed works above, the disadvantages in literature are as follows:

a) Existing works only considered user preferences when selecting network for MMT, such as [1]–[5], [20], [22], which causing the judgment to be too subjective.
b) Existing works only considered the service characteristics, such as [21], but ignored user preferences and therefore causing a bad user experience.
c) The existing solutions have shortcomings in combining with multiple factors while making network selection decision for MMT, so they cannot be considered as comprehensive MMT network selection algorithms.

Therefore, we propose a hybrid MMT network selection algorithm. Unlike previous works, which only considered a single factor, our algorithm not only considers the user preferences, service characteristics, and requirements, but also takes real-time network conditions into account. What's more, we use different types of utility functions and parameters to reflect the QoS requirements of different services. In addition, a threshold is used to enable the terminal to maintain the current connection as much as possible, which reduces VHO numbers while improving user's satisfaction, meeting services' requirements, and avoiding the ping-pong effect.

III. ALGORITHM IMPLEMENTATION

This section describes the three parts of network selection for MMT in a HWN in our algorithm, namely: comprehensive weight calculation, comprehensive utility value calculation, and the most appropriate network selection.

Section III.A describes the system and algorithm model of our MMT network selection algorithm. Section III.B, III.C, and III.D describe the computation of user-specified, service-determined, and objective weights of network attributes, respectively. These three aspects determine the final comprehensive weights of network attributes together. The calculation of comprehensive utility values of network attributes is described in section III.E. Section III.F and III.G describe the network ranking and the most appropriate network selection.

A. SYSTEM AND ALGORITHM MODEL

We assume that the MMT is in the HWN environment shown in Fig. 3. The MMT network selection problem in HWN shown in Fig. 3 can be defined as follows: given a set of candidate networks, $R = \{r_1, \ldots, r_{|R|}\}$, $|R| \geq 2$, and $S = \{s_1, \ldots, s_{|S|}\}$, $|S| \geq 1$ be the set of services supported in the HWN. The set of network attributes considered in making MMT network selection decision is $C = \{c_1, \ldots, c_N\}$, $N \geq 2$. A group of services (decision makers) $S^t = \left\{s_1^t, \ldots, s_g^t, \ldots s_Y^t\right\}$, $s_g^t \in S$, $Y \leq |S|$ (superscript t means a MMT, hereinafter the same) from one MMT select the optimal network from the candidate networks $R^t = \left\{r_1^t, \ldots, r_i^t, \ldots, r_M^t\right\}$, $r_i^t \in R$, $M \leq |R|$ that can support S^t. N, Y, M represent the number of attributes, services, and candidate networks respectively. Let $W^{t,U} = \left\{w_{g,j}^{t,U}\right\}$ (superscript U means user, hereinafter the same) be the set of user-specified weights, where $w_{g,j}^{t,U}$ represents the user-specified weight of attribute c_j for service s_g^t. Let $W^{t,S} = \left\{w_{g,j}^{t,S}\right\}$ (superscript S means service, hereinafter the same) be the set of service-determined weights where $w_{g,j}^{t,S}$ is the service-determined weight of attribute c_j for service s_g^t. Set $P^{t,U} = \left\{p_g^{t,U}\right\}$ and set $P^{t,S} = \left\{p_g^{t,S}\right\}$ indicate the user-specified and service-determined degree of priority of each service in set S^t respectively. In all the above descriptions, $g = 1, \ldots, Y$ and $j = 1, \ldots, N$. The network attributes used for decision making are bandwidth (c_1), delay (c_2), jitter (c_3), packet loss rate (c_4) and cost (c_5). The problem addressed in this paper is finding the most appropriate network $r_i^t \in R^t$ for admitting the set of services S^t.

The process of the entire algorithm is shown in Fig. 1. Firstly, the user specifies the network attributes weights $W^{t,U}$ and the service priority vector $P^{t,U}$ to represent the user's preferences. At the same time, the pairwise comparison matrix for each service is constructed according to the service characteristics. For example, the conversational class services have higher requirement on cost, delay and jitter, but are not sensitive to the packet loss rate within a certain range. For streaming class services, latency is not as important as bandwidth and jitter. Price and packet loss are also not very important attributes. As for interactive services, the packet loss rate has the highest priority and the latency and jitter are not very important. Use FAHP to calculate the network attribute weight vector $W_g^{t,S}$ determined by each service. These data above are stored in the MMT along with the objective service priority vector $P^{t,S}$. When making network selection decisions, MMT can use the GDM technology to calculate the user-specified weight vector W^U and the service-determined weight vector W^S according to the running service classes.

Secondly, MMT detects the attribute parameters of the candidate networks, constructs the network attribute matrix and normalizes it. Entropy is used to calculate the objective weight vector W^O (superscript O means objective, hereinafter the same) of the network attributes. W^O and the user-specified weight vector W^U along with the service-determined weight vector W^S are adjusted by the weight proportion parameters (i.e., α, β, and γ) to obtain the comprehensive weights of the network attributes. Each of these parameters represents the proportion of the corresponding factor.

TABLE 1. Service priority.

Service priority	value
very low	1
low	2
medium	3
high	4
very high	5

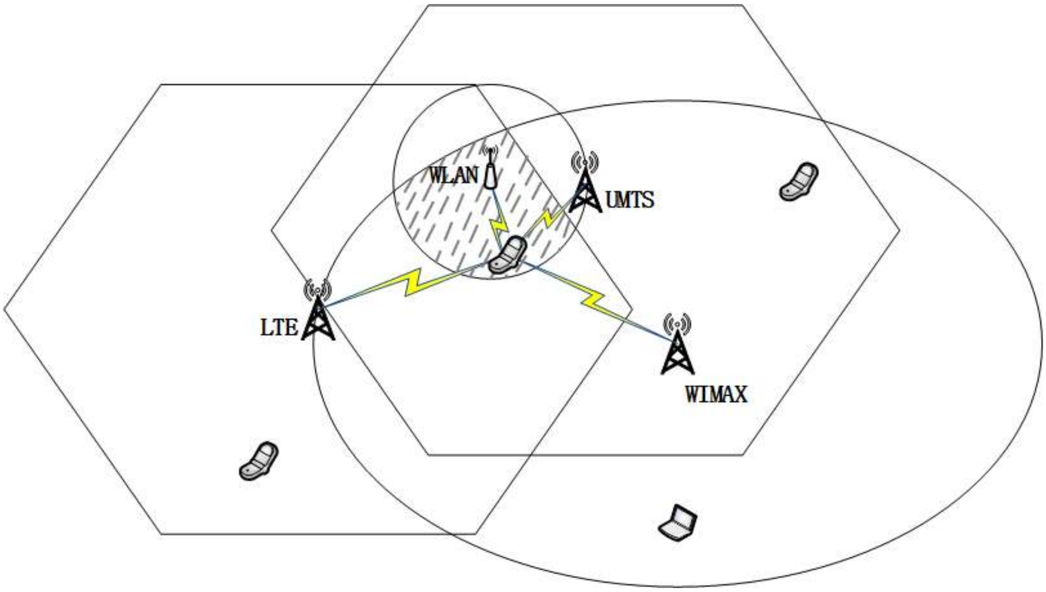


FIGURE 3. A HWN environment.

Then, according to the network attribute matrix and the objective requirements of each service for the network attributes, the utility functions are used to calculate the utility values of the network attributes for each service. The network attributes' comprehensive utility values for multiple services are obtained by synthesizing the objective service priority vector $P^{t,S}$ and network attributes utility values of each service.

Finally, the weighted decision matrix is constructed according to the comprehensive weights and utility values of network attributes. TOPSIS is used to calculate the closeness of the candidate networks to idea network. And depending on the threshold δ, MMT choose to connect to the target network or maintain the current network connection.

B. CALCULATE NETWORK ATTRIBUTES WEIGHTS DETERMINED BY USER PREFERENCES

The user's preferences information for each class of service are expressed as the weights assigned to the network attributes. The user-specified weight vector for each service is $W_g^{t,U} = \left\{ w_{g,j}^{t,U} \right\}$. Where $w_{g,j}^{t,U}$ represents the user-specified weight of attribute c_j for service s_g^t, and $w_{g,j}^{t,U}$ can be specified as [0, 9] ten point scale, where 0 means the least important and 9 means the most important. The priority values of services specified by user are shown in Table. 1, which indicate how important the service is to the user. The user-specified service priority vector is $P^{t,U} = \left\{ p_g^{t,U} \right\}$. Where $p_g^{t,U}$ represents the priority of service s_g^t. The specification of attributes' weights and priority of a service are done once and will always be used in selecting the network for a MMT. However, users can change these values based on their preferences.

Using the specified attributes weights and priority of each service, the algorithm can calculate the user-specified weights of network attributes for a group of services. The steps of calculating the user-specified network attributes weights for a group of services are as follows:

Step 1: Normalize the user-specified weight vector $W_g^{t,U}$ of service s_g^t using (1). $W_g^{t,U}$ represents the relative importance of the network attributes specified by user for service s_g^t, and it is given as:

$$W_g^{t,U} = \left\{ w_{g,1}^{t,U}, \ldots, w_{g,j}^{t,U}, \ldots, w_{g,N}^{t,U} \right\}, \quad g = 1, \ldots, Y.$$

$W_g^{t,U}$ is normalized as follows:

$$\begin{aligned} \overline{W}_g^{t,U} &= \left\{ \overline{w}_{g,1}^{t,U}, \ldots, \overline{w}_{g,j}^{t,U}, \ldots, \overline{w}_{g,N}^{t,U} \right\} \\ \overline{w}_{g,j}^{t,U} &= \frac{w_{g,j}^{t,U}}{\sum_{j=1}^{N} w_{g,j}^{t,U}}. \end{aligned} \tag{1}$$

TABLE 2. Membership function of fuzzy number.

No.	Definition	TFN	Reciprocal of TFN
1	Equal Importance	(1, 1, 3)	(1, 1, 0.33)
2	Intermediate Values	(1, 2, 4)	(0.25, 0.5, 1)
3	Moderate Importance	(1, 3, 5)	(0.2, 0.33, 1)
4	Intermediate Values	(2, 4, 6)	(0.17, 0.25, 0.5)
5	Strong Importance	(3, 5, 7)	(0.14, 0.2, 0.33)
6	Intermediate Values	(4, 6, 8)	(0.125, 0.17, 0.25)
7	Very Strong Importance	(5, 7, 9)	(0.11, 0.14, 0.2)
8	Intermediate Values	(6, 8, 9)	(0.11, 0.125, 0.17)
9	Extreme Importance	(7, 9, 9)	(0.11, 0.11, 0.14)

Step 2: Normalize the user-specified service priority vector, $P^{t,U}$.

$$P^{t,U} = \left\{p_1^{t,U}, \ldots, p_g^{t,U}, \ldots, p_Y^{t,U}\right\}, \quad g = 1, \ldots, Y$$

Normalize $P^{t,U}$ to get $\overline{P}^{t,U}$ by (2).

$$\begin{aligned} \overline{P}^{t,U} &= \{\overline{p}_1^{t,U}, \ldots, \overline{p}_g^{t,U}, \ldots, \overline{p}_Y^{t,U}\} \\ \overline{p}_g^{t,U} &= \frac{p_g^{t,U}}{\sum_{g=1}^{Y} p_g^{t,U}} \end{aligned} \tag{2}$$

Step 3: Synthesize the normalized weight vector $\overline{W}_g^{t,U}$ of network attributes for each service and the normalized service priority vector $\overline{P}^{t,U}$. Then obtain the user-specified weight vector W^U of network attributes for a group of services by (3).

$$\begin{aligned} W^U &= \{w_1^U, \ldots, w_j^U, \ldots, w_N^U\} \\ w_j^U &= \sum_{g=1}^{Y} \overline{w}_{g,j}^{t,U} * \overline{p}_g^{t,U} \end{aligned} \tag{3}$$

where Y is the number of running services in the MMT, $\overline{p}_g^{t,U}$ is the normalized priority value of service s_g^t, and $\overline{w}_{g,j}^{t,U}$ is the normalized weight of attribute c_j for service s_g^t. w_j^U is the weight of attribute c_j for a group of services specified by user.

C. USE FAHP TO CALCULATE THE SERVICE-DETERMINED NETWORK ATTRIBUTES WEIGHTS

AHP cannot express the fuzziness of preferences. To solve this problem, van Laarhoven and Pedrycz [23] applied fuzzy logic to AHP and proposed FAHP. FAHP can handle uncertainty and fuzziness between decision criteria by using fuzzy sets or fuzzy numbers. Therefore, we use FAHP to calculate the service-determined weights of network attributes. FAHP constructs a decision-making problem into different hierarchies. And the comparison of decision criteria for each layer are fuzzy numbers.

We use triangular fuzzy numbers (TFNs) to represent the fuzziness of preferences. The TFN is defined as M = (l, m, u), l ≤ m ≤ u, where l, m, u represent the lower limit value, the most favorable value and the upper limit value expressed by the decision maker respectively. The fuzzy number becomes a real number when l = m = u. The correspondence between the importance of the attributes and the TFN is shown in Table. 2. A form of TNF is defined as (4) [16].

$$\mu_{\widetilde{N}(x)} = \begin{cases} \dfrac{x-l}{m-l} & l \le x \le m \\ \dfrac{u-x}{u-m} & m \le x \le u \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

The calculation rules of TFNs are shown as (5), (6), and (7). Where M_1 and M_2 are two TFNs. And $M_1 = (l_1, m_1, u_1)$, $M_2 = (l_2, m_2, u_2)$.

$$M_1 + M_2 = (l_1 + l_2, m_1 + m_2, u_1 + u_2) \tag{5}$$

$$M_1 \otimes M_2 = (l_1 \times l_2, m_1 \times m_2, u_1 \times u_2) \tag{6}$$

$$\frac{1}{M_1} = \left(\frac{1}{u_1}, \frac{1}{m_1}, \frac{1}{l_1}\right) \tag{7}$$

The objective priority vector of the multiservice is $P^{t,S} = \left\{p_g^{t,S}\right\}, g = (1, \ldots, Y)$. $p_g^{t,S}$ is the priority of the service s_g^t among a group of services determined by the service characteristics. In this paper, $P^{t,S}$ is considered to be the same as $P^{t,U}$, and their normalization methods are also the same. After normalization, the priority vector determined by services is $\overline{P}^{t,S} = \{\overline{p}_1^{t,S}, \ldots, \overline{p}_g^{t,S}, \ldots, \overline{p}_Y^{t,S}\}$.

The service-determined attributes weights $W_g^{t,S}$, $(g = 1, \ldots, Y)$ of each service are calculated by FAHP firstly, then synthesize $W_g^{t,S}$ and $\overline{P}^{t,S}$ to obtain the service-determined attributes weights of a group of services. The six steps of calculating the service-determined network attributes weights by using FAHP are as follows:

Step 1: Construct the hierarchy of the MMT network selection problem. Fig. 4 shows the FAHP hierarchy of this decision problem.

Step 2: Construct a fuzzy comparison matrix A^g $(g = 1, \ldots, Y)$ for service s_g^t as shown in (8), Y is the number of services run by the MMT, and n is the number of network attributes (n = N).

$$A^g = \left(a_{ij}\right)_{n \times n} \tag{8}$$

where $a_{ij} = (l_{ij}, m_{ij}, u_{ij})$ is the importance of attribute c_i relative to attribute c_j for service s_g^t. When i ≠ j, $a_{ji} = 1/a_{ij}$, else $a_{ii} = (1, 1, 1)$.

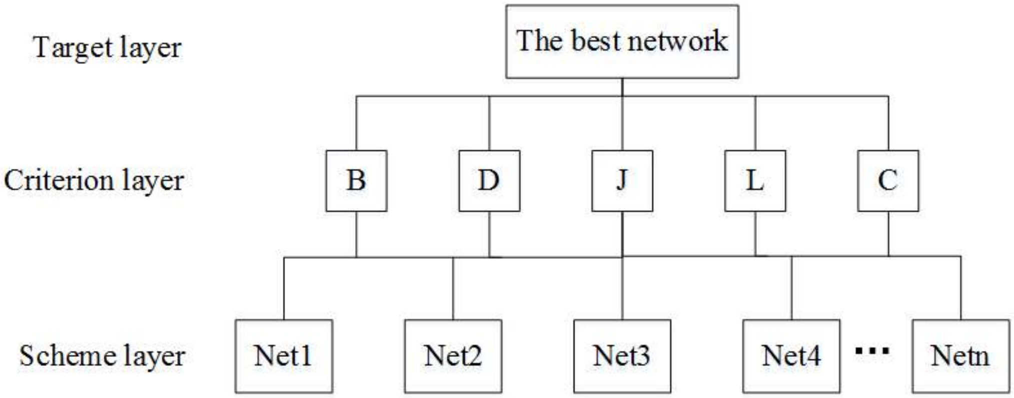


FIGURE 4. FAHP hierarchy of the MMT network selection decision problem.

Step 3: Calculate the comprehensive fuzzy value S_i of the attribute c_i according (9).

$$S_i = \sum_{j=1}^{n} \alpha_{ij} \otimes \left[\sum_{i=1}^{n}\sum_{j=1}^{n}\alpha_{ij}\right]^{-1} \tag{9}$$

where, $\sum_{j=1}^{n} \alpha_{ij} = (\sum_{j=1}^{n} l_{ij}, \sum_{j=1}^{n} m_{ij}, \sum_{j=1}^{n} u_{ij})$, and

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{n}\alpha_{ij}\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{n} u_{ij}}, \frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{n} m_{ij}}, \frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{n} l_{ij}}\right).$$

And S_i is a TNF where $S_i = (l_i, m_i, u_i)$.

Step 4: Calculate the probability $\mathrm{V}(S_j \geq S_i)$ that the comprehensive fuzzy value S_j is larger than S_i by (10). S_j and S_i are the comprehensive fuzzy values of the attributes c_j and c_i calculated from Step 3, respectively, and $j \neq i$.

$$\mathrm{V}\left(S_j \geq S_i\right) = \begin{cases} 1 & m_j \geq m_i \\ \dfrac{l_j - u_i}{\left(m_j - u_j\right) - \left(m_i - l_i\right)} & m_j \leq m_i,\ l_i \leq u_j \\ 0 & other \end{cases} \tag{10}$$

Step 5: Calculate the weight value $w_{g,j}^{t,S}$ of network attribute c_j for service s_g^t. First calculate the initial weight $w_{g,j}^{t,S\prime}$ of attribute c_j by (11).

$$w_{g,j}^{t,S\prime} = minV\left(S_j \geq S_i\right) = minV\left(S_j \geq S_1, S_2, \ldots, S_N\right), \quad j = 1, \ldots, N \tag{11}$$

Then normalize the initial weight $w_{g,j}^{t,S\prime}$ by (12) and obtain the normalized weight $w_{g,j}^{t,S}$ of attribute c_j determined by service s_g^t to satisfy $\sum_{j=1}^{n} w_{g,j}^{t,S} = 1$.

$$w_{g,j}^{t,S} = \frac{w_{g,j}^{t,S\prime}}{\sum_{j=1}^{N} w_{g,j}^{t,S\prime}} \quad j = 1, \ldots, N \tag{12}$$

The final network attribute weight vector $W_g^{t,S} = \{w_{g,1}^{t,S}, w_{g,2}^{t,S}, \ldots, w_{g,N}^{t,S}\}$ determined by service s_g^t is obtained.

Step 6: Synthesize the network attribute weight vector $W_g^{t,S}$ of each service and the service priority vector $\overline{P}^{t,S}$ to get the network attribute weight vector W^S determined by the running services in a MMT by (13).

$$\begin{aligned} W^S &= \{w_1^S, \ldots, w_j^S, \ldots, w_N^S\} \\ w_j^S &= \sum_{g=1}^{Y} w_{g,j}^{t,S} * \overline{p}_g^{t,S} \end{aligned} \tag{13}$$

where $w_{g,j}^{t,S}$ is the weight of attribute c_j determined by service s_g^t calculate by (12), and $\overline{p}_g^{t,S}$ is the normalized priority value of s_g^t. w_j^S is the weight of attribute c_j for a group of services determined by services' characteristics.

D. USE ENTROPY TO CALCULATE THE OBJECTIVE WEIGHTS OF NETWORK ATTRIBUTES

Entropy is a measure of the disorder degree of a system. The smaller the entropy value of the criterion, the more information the criterion provides, the higher the weight of the criterion is when introduced into the weight calculation. Because there is no human-factor interference in the calculation process, entropy is often used to calculate the objective weight of decision criteria.

In this paper, we use entropy to calculate the objective weight vector W^O of network attributes. The steps are as follows:

Step 1: Construct network attribute matrix M^t as shown in (14).

$$M^t = \left(m_{ij}\right)_{M \times N} \tag{14}$$

where M is the number of candidate networks and N is the number of network attributes used for decision making. The element m_{ij} $(i = 1, \ldots M)$ $(j = 1, \ldots, N)$ of M^t is the value detected by MMT of attribute c_j, for network r_i^t.

Step 2: Normalize the matrix M^t.

Because there are incommensurability between different types of attributes, it is necessary to normalize M^t. M^t can be normalized by (15) and obtain $\overline{M}^t = (\overline{m}_{ij})_{M\times N}$.

$$\overline{m}_{ij} = \frac{m_{ij}}{\sum_{i=1}^{M} m_{ij}}, \quad j = 1, \ldots, N \tag{15}$$

Step 3: Calculate the network attribute objective weight vector $W^O = \{w_1^O, \ldots, w_j^O, \ldots, w_N^O\}$ by entropy. First use $\overline{M}^t$ obtained by (15) to calculate the entropy value of each attribute by (16).

$$E_j = -k \sum_{i=1}^{M} \overline{m}_{ij} \ln\left(\overline{m}_{ij}\right), \quad j = 1, \ldots, N \tag{16}$$

where k is a constant, here take $\frac{1}{\ln(M)}$, and M is the number of rows of M^t, that is, the number of candidate networks. E_j is the entropy value of attribute c_j. $\overline{m}_{ij}$ is the normalized value for network r_i^t on attribute c_j obtained by (15).

Then calculate the objective weight of attribute c_j by (17).

$$w_j^O = \frac{1 - E_j}{N - \sum_{j=1}^{N} E_j}, \quad j = 1, \ldots, N \tag{17}$$

where w_j^O is the objective weight of attribute c_j and N is the number of attributes.

The objective weight vector $W^O = \left\{w_1^O, \ldots, w_j^O, \ldots, w_N^O\right\}$ of network attributes is finally obtained.

In our algorithm, the comprehensive weights of the network attributes are determined by user preferences, network attributes and service characteristics. The user-specified weight vector W^U, service-determined weight vector W^S, and objective weight vector W^O calculated in Sections III.B, III.C, and III.D respectively are used to calculate the final comprehensive weight vector W of network attributes by using (18).

$$\begin{aligned} \mathrm{W} = [w_1, w_2, \ldots, w_N] &= \alpha * W^U + \beta * W^O + \gamma * W^S, \\ \alpha + \beta + \gamma &= 1, \quad \alpha, \beta, \gamma \in (0, 1) \end{aligned} \tag{18}$$

In (18), weight proportion parameters, i.e., α, β, and γ represent the proportion of user preferences, network attributes and service characteristics in the final comprehensive weight respectively. The proportion of each factor's weight can be adjusted with the change of α, β, and γ. On this point, we make the following discussion.

a) If $\alpha = 0$, then the comprehensive weights of the network attributes will not consider the user preferences. On the contrary, if $\alpha = 1$, then the comprehensive weights of the network attributes will only consider user preferences, entropy and FAHP will not work.

b) If $\beta = 0$, then the comprehensive weights of the network attributes will not include the objective weight, meaning that entropy will not work. If $\beta = 1$, then the objective weights of the network attributes are the final weights, meaning FAHP will not work.

c) If $\gamma = 0$, then the user preferences and the network attributes will determine the comprehensive weights of the network attributes, and service characteristics will not be considered, therefore FAHP will not work. If $\gamma = 1$, then the comprehensive weights of the network attributes will be only determined by the service characteristics, meaning entropy will not work.

According to the discussion above, in order to comprehensively consider multiple factors, none of the values of α, β, and γ could be 0 or 1, which means that the comprehensive weights of the network attributes are determined by the user preferences, network attributes and service characteristics together. Moreover, the weight proportion parameters (α, β, and γ) are larger than 0 and smaller than 1, and $\alpha+\beta+\gamma = 1$.

E. CALCULATE THE UTILITY VALUES OF NETWORK ATTRIBUTES FOR THE SERVICE BASED ON SERVICE REQUIREMENTS

Through the calculation of the above three subsections, the comprehensive weight vector W of the network attributes is obtained. Next, we need to calculate the comprehensive utility values of the network attributes that multiple services can obtain from each candidate network.

In micro-economics, utility means the ability of a good or service to satisfy a human need. An associated term is utility function which relates to the utility derived by a consumer from a good or service. Different consumers with different user preferences (tastes) will have different utility values for a same product. Thus, the individual preferences should be taken into account in the utility evaluation [24]. In a MMT, different services have different characteristics and QoS requirements. With the same candidate network, the satisfactions of different services are different. In order to reflect the requirements of different services on network attributes, we use utility functions to normalize network attributes.

Network attributes can be divided into benefit attributes and cost attributes. For benefit attribute, the larger the network attribute value is, the larger the utility value obtained, such as the bandwidth attribute used in this paper. For cost attribute, the larger the network attribute value is, the smaller the corresponding utility value is, such as delay, jitter, packet loss rate, and cost attributes used in this paper. Because different services have different QoS requirements and elasticities, this paper uses two types of utility functions to reflect this difference.

a) The sigmoid utility function is used when both upper and lower thresholds of attributes' QoS requirements exist. For benefit attribute, the utility function f (x) is defined as (19). And the utility function g(x) of cost attribute is defined as (20).

$$\mathrm{f}\,(\mathrm{x}) = \frac{1}{1 + e^{-a(\mathrm{x}\text{-}\mathrm{b})}} \tag{19}$$

where a is a constant coefficient, which tune the steepness of the function, the higher a is, the steeper of the function graph is. So we use different a values to model the different elasticities and QoS requirements of services. b is the "center" of the utility which is defined according to the upper and lower thresholds.

$$\mathrm{g}\,(\mathrm{x}) = 1 - \mathrm{f}\,(\mathrm{x}) \tag{20}$$

b) Linear utility function and inverse proportional function are used for attributes which have only one threshold. For benefit attribute, the utility function u (x) is defined as (21). And h (x) defined as (22) is the utility function of cost attribute.

$$\mathrm{u}\,(\mathrm{x}) = 1 - g/x \tag{21}$$

$$\mathrm{h}\,(\mathrm{x}) = 1 - gx \tag{22}$$

Both in (21) and (22), g is a constant coefficient that may vary with different attributes.

The detailed process of calculating utility values of network attributes for a group of services are as follows:

Firstly, calculate the utility values of the network attributes for each service according to the QoS requirements of the service and the network attribute matrix M^t obtained by (14). The QoS requirements, utility functions and its parameters (i.e., a, b, and g) used for attributes of each service are shown in Table. 3. Calculate and construct the network attribute utility value matrix U^g for service s_g^t as shown in (23).

$$U^g = (u_{ij}^g)_{M\times N} \tag{23}$$

where the normalized utility value u_{ij}^g $(1 \leq i \leq M)$ $(1 \leq j \leq N)$ represents the utility value of attribute c_j, candidate network r_i^t, for service s_g^t. And $u_{ij}^g \in [0, 1]$.

Second, integrate the network attribute utility value matrix $U^g (g = 1, \ldots, Y)$ of multiple services and the objective service priority vector $\overline{P}^{t,S}$ to obtain a comprehensive utility value matrix $\mathrm{U} = (u_{ij})_{M\times N}$ for a group of services by (24).

$$u_{ij} = \sum_{g=1}^{Y} u_{ij}^g * \overline{p}_g^{t,S}, \quad i = 1, \ldots, M, \; j = 1, \ldots, N \tag{24}$$

where u_{ij} is the comprehensive utility value of the candidate network r_i^t on attribute c_j for multiservice. $\overline{p}_g^{t,S}$ is the normalized priority of service s_g^t.

F. USE TOPSIS FOR NETWORK RANKING

TOPSIS is one of the typical multi-attribute decision making methods, which is developed by Hwang and Yoon [28] originally to determine the score of a candidate. The basic idea of TOPSIS is to evaluate the Euclidean distance between the candidate solution, the positive ideal solution (PIS) and the negative ideal solution (NIS). The selected alternative has the shortest distance from the PIS and the farthest distance from the NIS.

After obtaining the comprehensive weight vector W and the comprehensive utility value matrix U for a group of services, the process of calculating candidate networks' scores using TOPSIS is as follows:

Step 1: Construct the normalized decision matrix.

In this paper, the decision matrix is the comprehensive utility value matrix U obtained by (24). Since the utility value of the attribute normalized by the utility function is between [0, 1], no further normalization is needed.

Step 2: Construct the weighted normalized decision matrix D as shown in (25). D is obtained by synthesizing the comprehensive weight vector W obtained by (18) and the comprehensive utility value matrix U obtained by (24).

$$D = \left(d_{ij}\right)_{M\times N} \tag{25}$$

where,

$$d_{ij} = u_{ij} * w_j, \quad i = 1, \ldots, M, \; j = 1, \ldots, N. \tag{26}$$

and w_j is the comprehensive weight of attribute c_j obtained by (18), and u_{ij} is the comprehensive utility value of attribute c_j for network r_i^t obtained by (24).

Step 3: Determine the PIS D^+ and the NIS D^- according to (27a) and (27b) respectively.

$$\begin{aligned} D^+ &= \left[d_1^+, d_2^+, \ldots, d_j^+, \ldots, d_N^+\right], \\ d_j^+ &= \max\left\{d_{ij}, i = 1, \ldots, M\right\} \end{aligned} \tag{27a}$$

$$\begin{aligned} D^- &= \left[d_1^-, d_2^-, \ldots, d_j^-, \ldots, d_N^-\right], \\ d_j^- &= \min\left\{d_{ij}, i = 1, \ldots, M\right\} \end{aligned} \tag{27b}$$

d_j^+ and d_j^- indicates the ideal value and the worst value of the attribute c_j among all the candidate networks respectively. Since the benefit attributes and the cost attributes have been distinguished when calculating the utility value, there is no need to distinguish when determine the D^+ and D^-.

Step 4: Calculate the Euclidean distance S_i^+ and S_i^- of each candidate network r_i^t to D^+ and D^- by (28).

$$\begin{cases} S_i^+ = \sqrt{\sum_{j=1}^{N} \left(d_j^+ - d_{ij}\right)^2}, & i = 1, \ldots, M \\ S_i^- = \sqrt{\sum_{j=1}^{N} \left(d_{ij} d_j^-\right)^2}, & i = 1, \ldots, M \end{cases} \tag{28}$$

where d_{ij} is the element of D obtained by (26).

Step 5: Calculate the closeness of each candidate network to the PIS, $\mathrm{SC} = \{sc_1, \ldots, sc_i, \ldots, sc_M\}$. The score sc_i of the candidate network r_i^t is obtained by using (29).

$$sc_i = \frac{S_i^-}{S_i^- + S_i^+} \tag{29}$$

G. DETERMINE THE OPTIMAL NETWORK

The scores of the candidate networks calculated by TOPSIS by (29) reflect the pros and cons of the candidate networks, and the network with the highest score is the optimal network. However, switching too frequently can lead to waste of network resources, terminal energy consumption and ping-pong effect. In order to reduce unnecessary VHO caused by instantaneous changes of the network parameters, we introduce a threshold δ to reduce the number of handoffs, thereby reducing the ping-pong effect.

TABLE 3. QoS requirements, utility functions and parameters of multiple services [25]–[27].

Services/Attributes	Bandwidth(kbs)	Delay(ms)	Jitter(ms)	Loss Rate(%)	Cost
Voice	32-64	50-100	50-80	<30	<50
	f(x)	g(x)	g(x)	h(x)	h(x)
	a=0.25,b=48	a=0.1, b=75	a=0.185,b=65	g=1/30	g=1/50
Video	512-5000	75-150	40-70	<30	<50
	f(x)	g(x)	g(x)	h(x)	h(x)
	a=0.003,b=2000	a=0.1,b=112.5	a=0.175,b=55	g=1/30	g=1/50
web browsing	128-1000	250-500	10-150	<30	<50
	f(x)	g(x)	g(x)	h(x)	h(x)
	a=0.01,b=564	a=0.03,b=375	a=0.05,b=80	g=1/30	g=1/50

TABLE 4. Weight proportion parameters combinations and corresponding average gains.

Combination	α	β	γ	average gain
1	0.2	0.3	0.5	0.8432
2	0.3	0.2	0.5	0.8407
3	0.2	0.5	0.3	0.8471
4	0.3	0.5	0.2	0.8463
5	0.5	0.2	0.3	0.8402
6	0.5	0.3	0.2	0.8420
7	1/3	1/3	1/3	0.8430

If the MMT is in a state where no network is connected initially, the network with the highest score is selected. Otherwise, if the network has the highest score is r_i^t, its score is sc_i, the score of the network r_j^t (i $\neq$ j) to which MMT is currently connected is sc_j. If $\frac{sc_i}{sc_j} > \delta$, $\delta > 1$, it switches to the network r_i^t, otherwise the MMT maintains the current connection.

According to the algorithm introduced above, we can analyze the time and space complexity of the proposed MMT network selection algorithm. Our algorithm combines FAHP, entropy, TOPSIS and other methods, and its time and space complexity are greater than each independent algorithm. However, the network attributes weights of each service calculated by FAHP only need to be calculated once and stored in the MMT, so the time and space complexity of the algorithm are mainly determined by entropy and TOPSIS. Its time complexity is $O(N^3)$. As for its space requirement, it only needs to store the user-specified weight vectors, service-determined weight vectors, service priority vector, three weight proportion parameters, a threshold, and so on. Its space complexity is $O(N^2)$. Because the value of M (number of candidate networks) and N (number of network attributes) are very small (usually not more than 10), and today's multimode terminals have higher computing and storage capabilities, the complexity of the algorithm is acceptable and it can work on MMT in real time.

IV. EXPERIMENTAL SIMULATION AND ANALYSIS

In this section, we will verify and analyze our proposed MMT network selection algorithm, using MATLAB R2016a as a platform for simulation and experimentation. And the CPU of the computer we use is Intel Core i5-4570, 3.20GHZ, and the memory is 4.00GB. Consider three services from a MMT, voice (s_1^t), video (s_2^t) and web browsing (s_3^t). The experimental simulation environment is shown as Fig. 3. It consists of four networks: UMTS (r_1^t), LTE (r_2^t), WLAN (r_3^t), and WiMAX (r_4^t). The MMT is located in the common coverage area of the four networks, indicated by the shaded part in Fig. 3.

We evaluate our algorithm from three aspects. 1) We simulate the procedure of our MMT network selection algorithm at a specific time point T. 2) We simulate multiple network selections in different service priority scenes. 3) Compare our algorithm with the existing two MMT network selection algorithms in the dynamic simulation environment, to display the superiorities of our algorithm.

A. DETERMINATION OF THE WEIGHT PROPORTION PARAMETERS VALUES

In our algorithm, the values of the weight proportion parameters (i.e., α, β, and γ) are static and set by the network operator. The operator can set the same parameters values for all MMTs in a HWN, or set different parameters values for each MMT. The operator sets and adjusts these values according to policies or protocols. For comprehensive consideration, α, β, and γ cannot be 0 or 1 and are bigger than 0 and smaller than 1, and $\alpha + \beta + \gamma = 1$ as we discussed above. In this paper, the weight proportion parameters values of all MMTs are the same.

In order to determine more appropriate weight proportion parameters values combination, we design seven parameters combinations as shown in Table. 4. For each parameters combination, the MMT network selection is simulated for 1000 MMTs that run three services (i.e., s_1^t, s_2^t and s_3^t). The values of network attributes for candidate networks are obtained randomly according to the range shown in Table. 5. The user-specified weights of attributes are randomly obtained in the range [0, 9], and $P^{t,U} = P^{t,S} = \{3, 3, 3\}$. Table. 6-8 shows the fuzzy comparison matrices for each class of service and the corresponding network attributes

TABLE 5. Network attributes parameters [27].

	Bandwidth(kbps)	Delay(ms)	Jitter(ms)	Loss Rate(%)	Cost
UMTS	700-2000	10-50	5-15	2-10	5-35
LTE	800-4000	40-80	15-40	6-20	10-45
WLAN	1000-8000	70-100	30-70	4-15	0-20
WiMAX	900-6000	50-90	20-50	8-20	15-50

TABLE 6. Fuzzy comparison matrix and weights for voice service.

Voice	Bandwidth	Delay	Jitter	Loss Rate	Cost	Weight
Bandwidth	(1,1,3)	(0.25,0.5,1)	(0.17,0.25,0.5)	(1,2,4)	(0.125,0.17,0.25)	0.1020
Delay	(1,2,4)	(1,1,3)	(0.2,0.33,1)	(1,3,5)	(0.14,0.2,0.33)	0.1863
Jitter	(2,4,6)	(1,3,5)	(1,1,3)	(3,5,7)	(0.2,0.33,1)	0.3007
Loss Rate	(0.25,0.5,1)	(0.2,0.33,1)	(0.14,0.2,0.33)	(1,1,3)	(0.11,0.14,0.2)	0.0186
Cost	(4,6,8)	(3,5,7)	(1,3,5)	(5,7,9)	(1,1,3)	0.3924

TABLE 7. Fuzzy comparison matrix and weights for video service.

Video	Bandwidth	Delay	Jitter	Loss Rate	Cost	Weight
Bandwidth	(1,1,3)	(1,2,4)	(0.17,0.25,0.5)	(4,6,8)	(4,6,8)	0.3227
Delay	(0.25,0.5,1)	(1,1,3)	(0.14,0.2,0.33)	(1,3,5)	(1,3,5)	0.1837
Jitter	(2,4,6)	(3,5,7)	(1,1,3)	(5,7,9)	(5,7,9)	0.4312
Loss Rate	(0.125,0.17,0.25)	(0.2,0.33,1)	(0.11,0.14,0.2)	(1,1,3)	(1,1,3)	0.0312
Cost	(0.125,0.17,0.25)	(0.2,0.33,1)	(0.11,0.14,0.2)	(1,1,3)	(1,1,3)	0.0312

weights calculated by FAHP. The "gain" obtained from the most appropriate network is defined by (30), and the average gain of the 1000 MMTs for each parameters combination is shown in Table. 4. From Table. 4 we can see that the parameters combination 3 can obtain the maximum average gain. So in this paper, we set $\alpha = 0.2$, $\beta = 0.5$, $\gamma = 0.3$ to obtain the maximum gain.

$$Gain = \sum_{j=1}^{N} u_{ij} * w_j, \quad 1 \le i \le M \tag{30}$$

where i represents the sort of the most appropriate network r_i^t which is selected, N is the number of attributes, u_{ij} is the comprehensive utility value of attribute c_j for multiservice obtained by (24), w_j is the comprehensive weight of attribute c_j obtained by (18).

B. NETWORK SELECTION AT TIME POINT T

This section illustrates the network selection process of our proposed algorithm at a certain time point T to verify the correctness and rationality of our algorithm by selecting the most appropriate network from multiple candidate networks. The MMT runs three services: voice, video, and web at the same time, with the state in which no network is connected initially.

First calculate the comprehensive weights of network attributes composed by user-specified weight W^U, service-determined weight W^S, and the objective weight W^O.

Step 1: Calculate the user-specified weight vector W^U of multiservice. The user specifies the network attributes weights and services priorities of different services as follows:

$$\begin{aligned} W_1^{t,U} &= \{78233\}, \\ W_2^{t,U} &= \{94256\}, \\ W_3^{t,U} &= \{54293\}. \\ P^{t,U} &= \{333\}. \end{aligned}$$

Normalizing the weight vectors of different services by using (1):

$$\begin{aligned} \overline{W}_1^{t,u} &= \{0.3043\ 0.3478\ 0.087\ 0.1304\ 0.1304\}, \\ \overline{W}_2^{t,u} &= \{0.3462\ 0.1538\ 0.0769\ 0.1923\ 0.2308\}, \\ \overline{W}_3^{t,u} &= \{0.2174\ 0.1739\ 0.087\ 0.3913\ 0.1304\}. \end{aligned}$$

The normalized service priority vector is obtained by (2).

$$\overline{P}^{t,U} = \{0.33\ 0.33\ 0.33\}.$$

Obtain the weight vector of the network attributes specified by the user using (3).

$$W^U = \{0.2893\ 0.2252\ 0.0836\ 0.238\ 0.1639\}.$$

Step 2: Use FAHP to calculate the weight vector W^S of network attributes determined by the services.

Table. 6-8 show the fuzzy comparison matrices for each class of service and the corresponding network attributes weights calculated by FAHP.

The service priority vector $P^{t,S} = \{3, 3, 3\}$. Synthesize the normalized priority vector $\overline{P}^{t,S}$ and the network attribute weight vectors determined by each service, the network attributes weights determined by multiservice are obtained by (13).

$$W^S = \{0.2422\ 0.1539\ 0.2459\ 0.1329\ 0.2251\}.$$

TABLE 8. Fuzzy comparison matrix and weights for web browsing.

Web	Bandwidth	Delay	Jitter	Loss Rate	Cost	Weight
Bandwidth	(1,1,3)	(3,5,7)	(4,6,8)	(0.25,0.5,1)	(1,2,4)	0.3021
Delay	(0.14,0.2,0.33)	(1,1,3)	(1,2,4)	(0.125,0.17,0.25)	(0.17,0.25,0.5)	0.0916
Jitter	(0.125,0.17,0.25)	(0.25,0.5,1)	(1,1,3)	(0.11,0.14,0.2)	(0.14,0.2,0.33)	0.0057
Loss Rate	(1,2,4)	(4,6,8)	(5,7,9)	(1,1,3)	(1,3,5)	0.3490
Cost	(0.25,0.5,1)	(2,4,6)	(3,5,7)	(0.2,0.33,1)	(1,1,3)	0.2515

TABLE 9. Network parameters at time point T.

	Bandwidth(kbps)	Delay(ms)	Jitter(ms)	Loss Rate(%)	Cost
UMTS	1000	40	13	10	31
LTE	1815	51	29	14	44
WLAN	2103	99	68	5	16
WiMAX	1624	67	47	17	39

TABLE 10. Utility values of attributes for voice service.

Voice	B	D	J	L	C
UMTS	1	0.9707	0.9999	0.6667	0.38
LTE	1	0.9168	0.9987	0.5333	0.12
WLAN	1	0.0832	0.3647	0.8333	0.68
WiMAX	1	0.6900	0.9654	0.4333	0.22

TABLE 11. Utility values of attributes for video service.

Video	B	D	J	L	C
UMTS	0.0474	0.9993	0.9994	0.6667	0.38
LTE	0.3647	0.9979	0.9895	0.5333	0.12
WLAN	0.5766	0.7941	0.0932	0.8333	0.68
WiMAX	0.2445	0.9895	0.8022	0.4333	0.22

Step 3: Calculate the objective weight W^O of the network attributes using entropy. Table. 9 shows the attributes' values of the candidate networks randomly obtained at time point T according to Table. 5.

First construct and normalize the network attributes matrix by using (15).

$$\overline{M}^t = \begin{bmatrix} 0.1529 & 0.1556 & 0.0828 & 0.2174 & 0.2385 \\ 0.2774 & 0.1984 & 0.1847 & 0.3043 & 0.3385 \\ 0.3215 & 0.3852 & 0.4331 & 0.1087 & 0.1231 \\ 0.2482 & 0.2607 & 0.2994 & 0.3696 & 0.3000 \end{bmatrix}$$

Then use entropy to calculate the objective weight vector W^O of the network attributes by using (16) and (17):

$$W^O = \{0.0868\ 0.1534\ 0.3831\ 0.2210\ 0.1557\}\,.$$

Step 4: The comprehensive weight vector W of the network attributes is obtained by synthesizing W^U, W^S, and W^O using (18). Where, $\alpha = 0.2$, $\beta = 0.5$, $\gamma = 0.3$.

$$\mathrm{W} = \{0.1739\ 0.1679\ 0.2820\ 0.1980\ 0.1781\}.$$

Then we should calculate the comprehensive utility values of the network attributes for multiservice.

Step 5: Calculate the utility values of the network attributes for each service. The utility functions and corresponding parameters of each service are shown in Table. 3. Table. 10-12 show the utility values of the network attributes for each service. The comprehensive utility value matrix U for multiservice is obtained by using (24).

$$\mathrm{U} = \begin{bmatrix} 0.6783 & 0.9900 & 0.9885 & 0.6667 & 0.38 \\ 0.7882 & 0.9715 & 0.9719 & 0.5333 & 0.12 \\ 0.8589 & 0.6257 & 0.3679 & 0.8333 & 0.68 \\ 0.7482 & 0.8931 & 0.8688 & 0.4333 & 0.22 \end{bmatrix}$$

Step 6: At last, use TOPSIS to calculate candidate networks' scores and select the most appropriate network. The weighted decision matrix D is constructed according to (26).

$$D = \begin{bmatrix} 0.1181 & 0.1662 & 0.2788 & 0.1320 & 0.0677 \\ 0.1371 & 0.1631 & 0.2471 & 0.1056 & 0.0214 \\ 0.1494 & 0.1051 & 0.1037 & 0.1650 & 0.1211 \\ 0.1301 & 0.1500 & 0.2450 & 0.0858 & 0.0392 \end{bmatrix}$$

Then, using TOPSIS, the score of each candidate network is calculated by using (27), (28), and (29), $SC = [0.7368\ \ 0.6091\ \ 0.4144\ \ 0.5522]$, i.e., $r_1^t > r_2^t > r_4^t > r_3^t$, so the optimal network selected is UMTS.

From the experimental result we can see that although the bandwidth of UMTS is smaller than that of the other three networks, it is still selected as the optimal network. This is because the jitter and delay attributes of LTE, WLAN, and WiMAX are much higher than UMTS, they are not suitable

TABLE 12. Utility values of attributes for web browsing service.

Web browsing	B	D	J	L	C
UMTS	0.9874	1	0.9661	0.6667	0.38
LTE	1	0.9999	0.9276	0.5333	0.12
WLAN	1	0.9997	0.6457	0.8333	0.68
WiMAX	1	0.9999	0.8389	0.4333	0.22

TABLE 13. Service priority values for three services.

Service	Service priority Scene						
	1	2	3	4	5	6	7
Voice	5	5	1	3	1	3	5
Video	1	3	5	5	3	1	5
Web browsing	3	1	3	1	5	5	5

for real-time services such as voice and video. As for the WLAN network, since it has the largest bandwidth and the lowest cost and suitable packet loss rate for interactive services such as web browsing, is not the optimal network either. Because the MMT in this experiment runs three services, and each service has the same priority, the WLAN network has the largest jitter and delay, so it is not as suitable as the optimal network. Therefore, in a single MMT network selection problem, our algorithm makes an appropriate selection, reflecting its correctness and rationality.

C. NETWORK SELECTION OF MMT IN DIFFERENT SERVICE PRIORITY SCENES

This section shows the network selection of MMTs under different service priority scenes to show the effectiveness of our algorithm. Table. 13 shows the seven priority scenes we designed. For example, in scene 1, the priority of voice, video, and web services is 5, 1, and 3 respectively. Voice and video have the lowest and highest priority, respectively. For each priority scene (scene1- scene7), we simulate the network selection of 1000 MMTs, which connect no network and run three services simultaneously. The values of candidate networks' attributes are randomly obtained according to Table. 5. In each scene, the services' priority values for all the 1000 MMTs are the same, the network attributes weights determined by the service characteristics are the same as shown in Table. 6-8, but the randomly-generated user-specified weights of network attributes for different services are different, and the weights determined by the network characteristics are also different.

Fig. 5 shows the percentage of each network selected by the 1000 MMTs in each service priority scene. From the figure, we can see that:

- In scene 1 and scene 2, the UTMS network has the greatest selected percentage.
- In scene 3 and scene 4, WLAN network has the greatest percentage of selection.
- In scene 5, the percentage of WLAN networks is much larger than UMTS.

These are because in scene 1 and scene 2, voice service has the highest priority, so the UTMS network with the lowest jitter and latency has the greatest selected percentage. In scene 3 and scene 4, video service has the highest priority, so the WLAN network characterized by high bandwidth has the greatest percentage of selection. In scene 5, web service and video have the highest and lowest priority, respectively, so the selection percentage of WLAN network, which has the largest bandwidth and a lower packet loss rate that is much larger than that of UMTS's. From the simulation results, we can conclude that while considering the users' preferences and the services' characteristics and requirements, the service priority has a significant impact on the network selection of MMT, which shows the effectiveness of our algorithm. At the same time our algorithm avoids inappropriate network selection due to user's too subjective preferences.

D. PERFORMANCE COMPARISON

In order to verify the superiorities of our proposed algorithm, we compare it with the MMT network selection algorithms proposed in [3] and [21] (hereinafter referred to as Fuzzy MCDGM and Utility-GDM, respectively) from four aspects: selection probability of candidate network, gain of network selection, handoff numbers and unnecessary handoff probability. In all the following comparative experiments, we assume that the user prefers the high-bandwidth and low-cost network, the user-specified attributes weights of each service are as shown in Table. 14. The values of network attributes for candidates are randomly obtained by MTALAB according to Table. 5. The MMT runs three services: voice, video and web browsing, and the service-specified weights of attributes for each class of service are shown as Table. 6-8. To be fair, the user-specified network attributes weights used by Fuzzy MCDGM are the same as our algorithm. The network attributes weights determined by each service used by Utility-GDM are the same as our algorithm, and the three algorithms use the same services priorities. Moreover, due to the different aspects considered in different algorithm, the selection results are different. For a certain requirement of user, some results are more reasonable. We compare

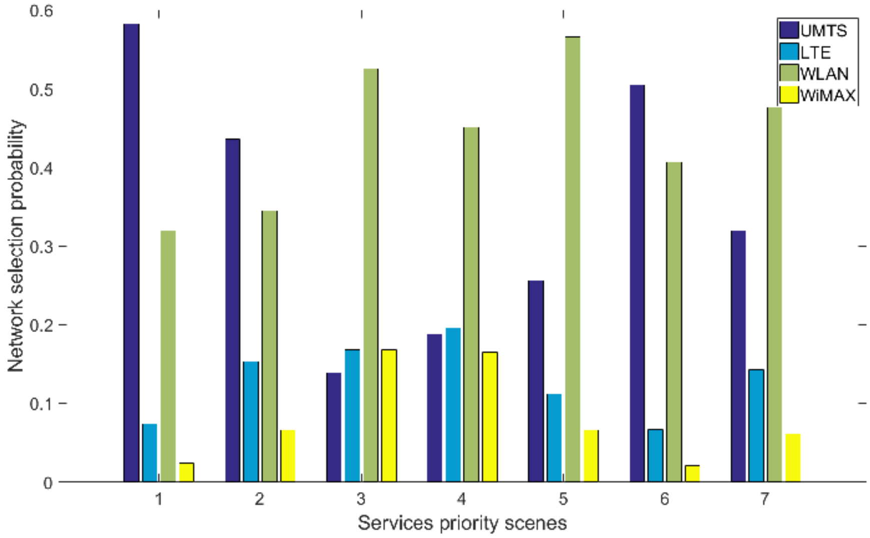


FIGURE 5. Network selection probability of MMTs in different service priority scenes.

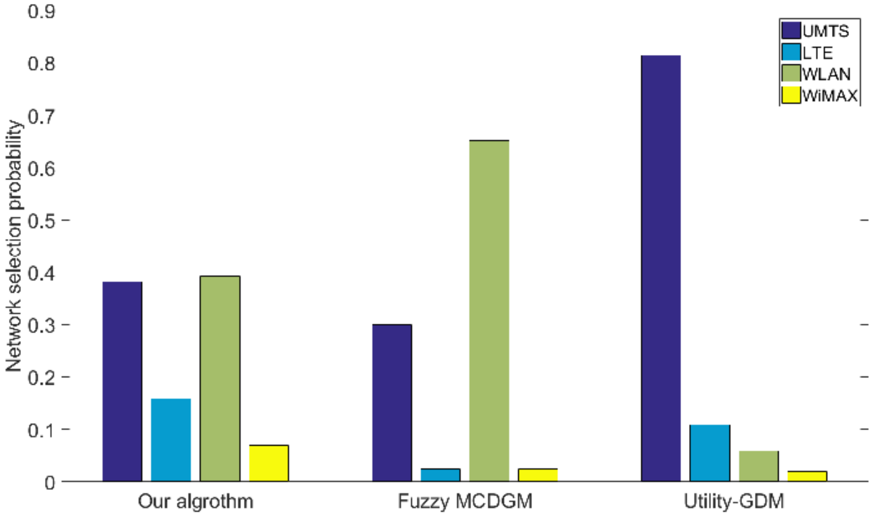


FIGURE 6. Network selection probability of three MMT network selection algorithms.

the results of the three algorithms in this part. Because the dynamics of the HWN environment, the specific values of the results of each experiment are different, but we can analyze the trend of one algorithm from its statistic result. All the result values of the experiment are obtained by MATLAB simulation.

Firstly, we compare the network selection of the three algorithms. The priority of each service uses scene 2 in Table. 13, that is, the priority of voice, video, and web is 5, 3, and 1, respectively. We simulated 1000 MMTs network selections for each algorithm in MATLAB, each MMT is in an initial state where no network is connected. Fig. 6 shows the probability that each network is selected in each algorithm:

- In our algorithm, the selection probabilities of UTMS and WLAN are 0.381 and 0.392 respectively.
- In Fuzzy MCDGM, the WLAN network has the highest selection probability of 0.652, which is 2.2 times of UMTS.
- In Utility-GDM, the UMTS has the highest selection probability of 0.814, which far exceeds other networks.

We analyze the results of the simulation, because Fuzzy MCDGM only considers the user's preferences, and the user prefers the high-bandwidth and low-price network, so the WLAN network, which has the highest bandwidth and lowest cost, has the highest selection probability. In Utility-GDM, only the characteristics of the services are considered. The voice service, which has highest priority, requires low jitter and low cost, and the video service, which has higher priority, requires low latency and low jitter, so the UMTS network with lower cost and lowest delay and jitter has the highest selection probability. In our algorithm, we not only consider the user's preferences and the services' characteristics, but also consider the actual network environment and the services' QoS requirements, so WLAN and UMTS have almost the same selection probability. We avoid the user's subjective judgment that ignores the objective requirements of the services, and

TABLE 14. User-specified network attributes weights.

Services/weight	**B**	**D**	**J**	**L**	**C**
voice	9	3	5	4	8
video	9	4	2	3	8
web browsing	8	4	3	5	9

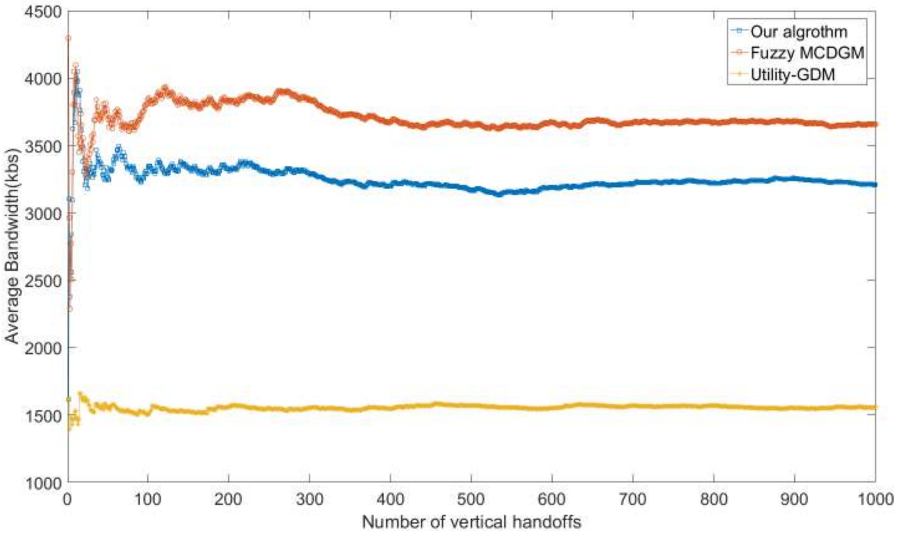


FIGURE 7. Average bandwidth of the optimal network.

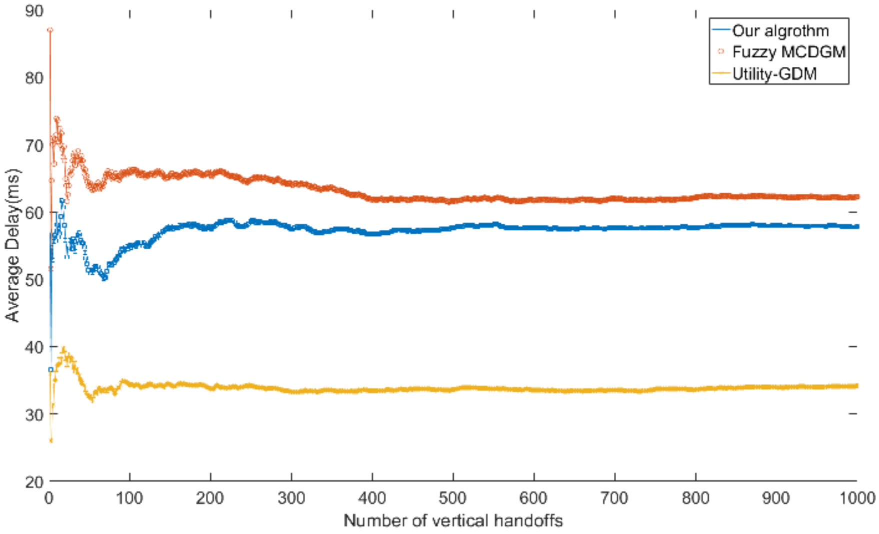


FIGURE 8. Average delay of the optimal network.

add user's subjective preferences to the objective judgment, thereby improving the user's experience while satisfying the services' requirements. At the same time, it helps maintain the load balance of the system and avoid the network congestion caused by excessive MMTs selecting the same network.

Apart from the selection probability above, the quantified benefits from the most appropriate network are also obtained from the above simulation. Fig. 7-11 show the average bandwidth, delay, jitter, packet loss rate, and cost of the most appropriate network selected by the three algorithms over these 1000 MMTs network selections respectively. From these figures, we can see that:

- Fuzzy MCDGM achieves the largest average bandwidth and lowest average cost, as shown in Fig. 7 and Fig. 11 respectively.

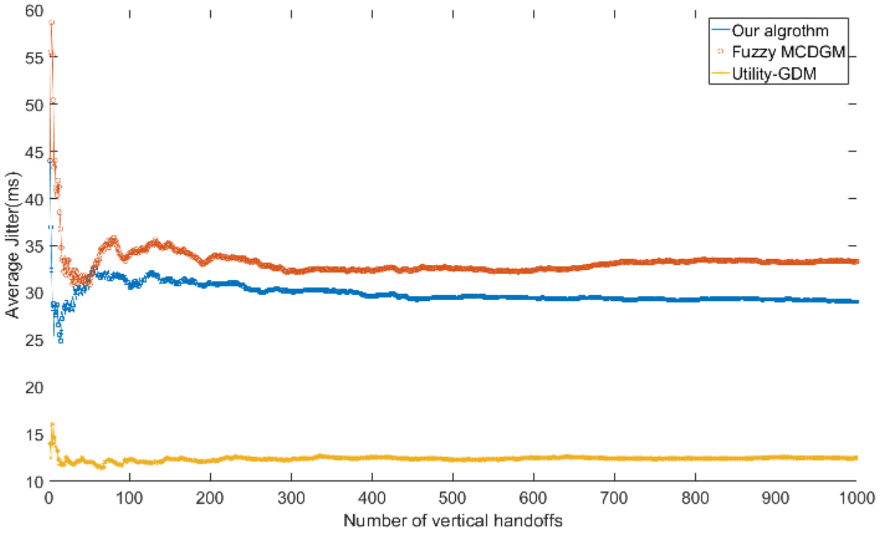


FIGURE 9. Average jitter of the optimal network.

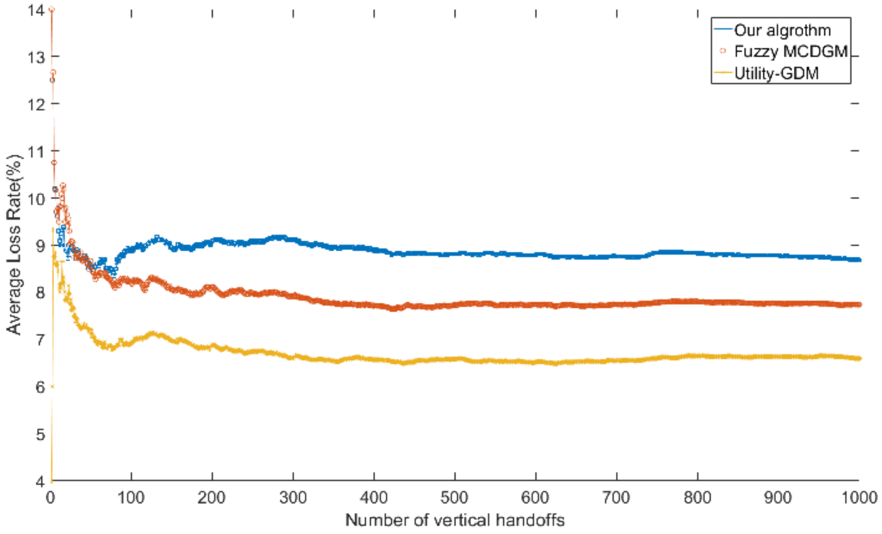


FIGURE 10. Average packet loss rate of the optimal network.

- Utility-GDM achieves the lowest average delay and jitter obtained, as shown in Fig. 8 and Fig. 9.
- Our algorithm achieves the highest average loss rate as shown in Fig. 10.

Since users prefer networks with high bandwidth and low cost, and services require low latency and low jitter networks, Fuzzy MCDGM prefer WLAN network and Utility-GDM selects UMTS most as shown in Fig. 6. As a result, Fuzzy MCDGM achieves the largest average bandwidth and lowest average cost, and the average delay and jitter obtained by Fuzzy MCDGM are greater than those of Utility-GDM's. Our algorithm takes into consideration both user preferences and service characteristics, so the average bandwidth, cost, latency, and jitter obtained are between those of Fuzzy MCDGM and Utility-GDM. As for average loss rate, because LTE and WiMAX that have the higher loss rate have higher selection probabilities in our algorithm, the average loss rate in our algorithm is the highest as shown in Fig. 10. In these 1000 MMT network selection simulation, although the quality of our algorithm is not the best on a single attribute, as shown in Fig. 7-11, the average overall gain defined by (30) a MMT obtained from the most appropriate network of our algorithm is the highest, with a score of 0.8460 while Fuzzy MCDGM being 0.8164 and Utility-GDM being 0.8292. So the overall gain of our algorithm has an advantage over those of two other algorithms. This shows that although considers different factors, our algorithm performs better than the other two algorithms. And we take into account user preferences and service requirements.

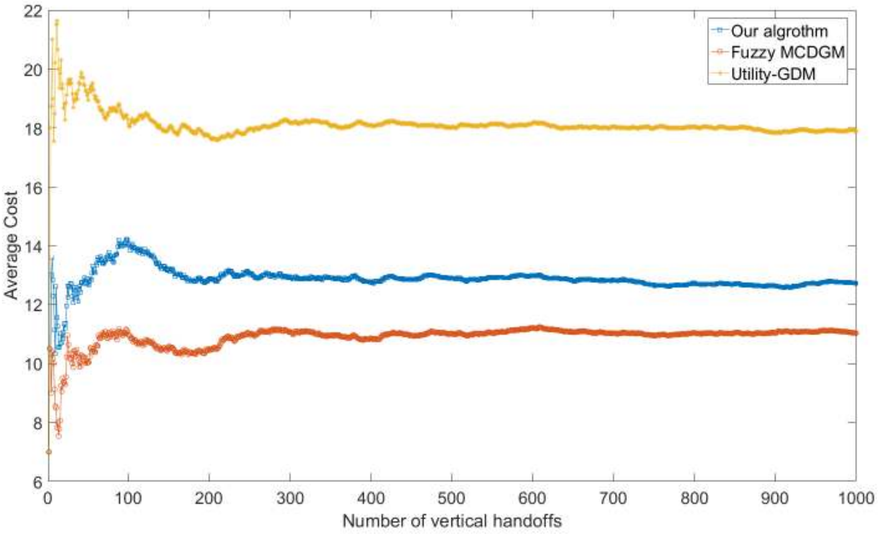
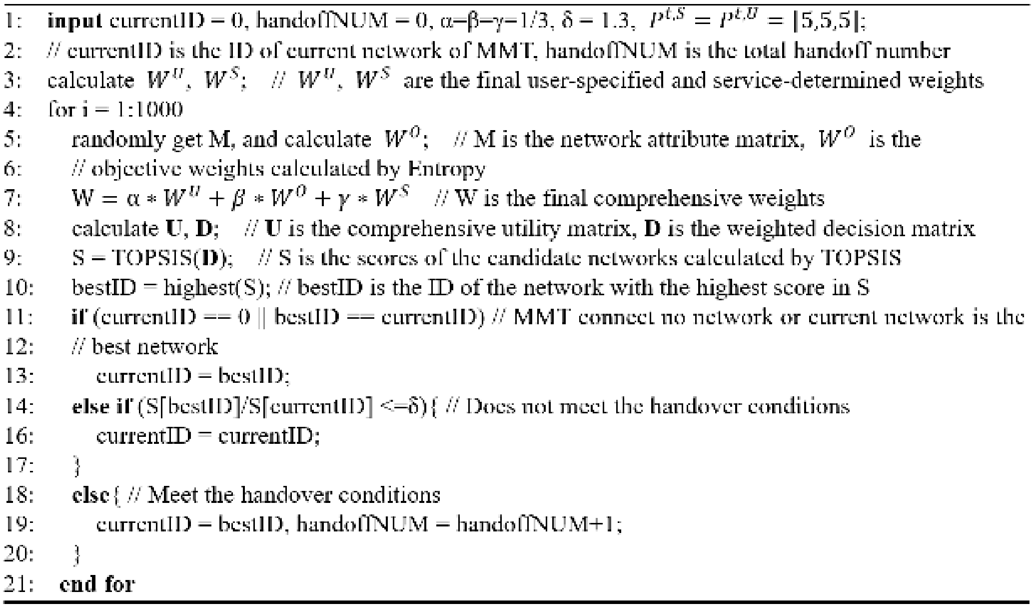


FIGURE 11. Average cost of the optimal network.



```
input currentID = 0, handoffNUM = 0, α=β=γ=1/3, δ = 1.3, $P^{t,S} = P^{t,U}$ = [5,5,5];
// currentID is the ID of current network of MMT, handoffNUM is the total handoff number
calculate $W^U$, $W^S$;   // $W^U$, $W^S$ are the final user-specified and service-determined weights
for i = 1:1000
    randomly get M, and calculate $W^O$;   // M is the network attribute matrix, $W^O$ is the
    // objective weights calculated by Entropy
    W = $\alpha * W^U + \beta * W^O + \gamma * W^S$   // W is the final comprehensive weights
    calculate U, D;   // U is the comprehensive utility matrix, D is the weighted decision matrix
    S = TOPSIS(D);   // S is the scores of the candidate networks calculated by TOPSIS
    bestID = highest(S); // bestID is the ID of the network with the highest score in S
    if (currentID == 0 || bestID == currentID) // MMT connect no network or current network is the
    // best network
        currentID = bestID;
    else if (S[bestID]/S[currentID] <=δ){ // Does not meet the handover conditions
        currentID = currentID;
    }
    else{ // Meet the handover conditions
        currentID = bestID, handoffNUM = handoffNUM+1;
    }
end for
```

FIGURE 12. Pseudo code to calculate the number of vertical handoff of our algorithm.

Then, in order to verify the performance of VHO for each algorithm, we simulated 1000 network selections of a MMT in MATLAB. The three services have the same priority. User preferences, network attributes, and service characteristics have the same weight proportion, that is, $\alpha = \beta = \gamma = 1/3$. The threshold used in our algorithm is $\delta = 1.3$ (appropriate value determined by experiment). Obviously, the bigger the δ is, the number of unnecessary handovers is smaller. The relevant pseudo-code of our algorithm is described in Fig. 12. From Fig. 13, it can be seen that:

- The numbers of vertical handoffs of the three algorithms all increase with the time.
- Our algorithm and Fuzzy MCDGM are the slowest and fastest, respectively.

This is because our algorithm uses a threshold δ to avoid unnecessary handovers. At the same time, we consider user preferences, network attributes and service characteristics, avoiding frequent handover of MMTs due to the instantaneous changes of network parameters. Therefore, our algorithm has a significant effect in reducing the number of vertical handoff.

In addition to the number of vertical handoff, in order to compare the unnecessary handoff probabilities of the three MMT network selection algorithms, we simulated

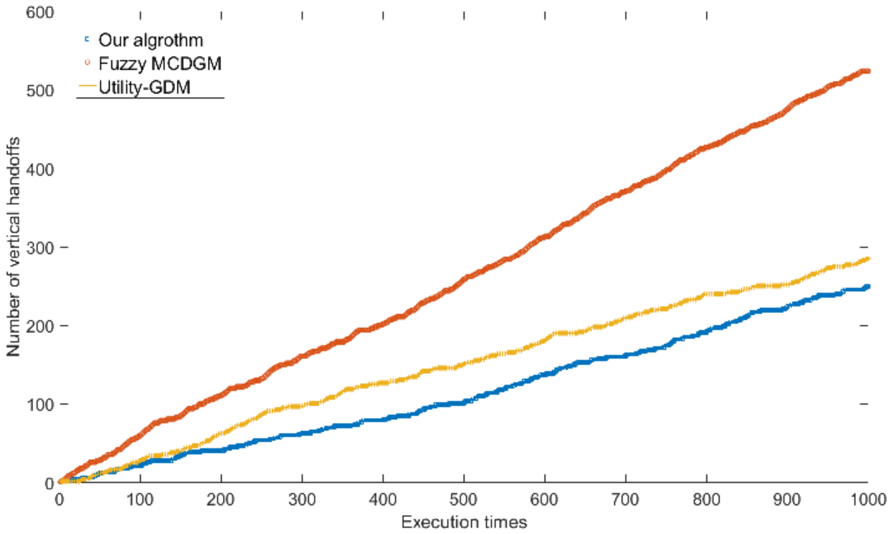


FIGURE 13. Number of vertical handoffs for three MMT network selection algorithms.

```
input α=β=γ=1/3, δ = 1.3, $P^{t,S} = P^{t,U}$ = [5,5,5];
old_ID = old_old_ID = 0, Unnecessary_count = Total_count=0, last_last_time=last_time = 0;
/* old_ID, old_old_ID are the IDs of the current and last connected network. Unnecessary_count,
Total_count are the numbers of unnecessary handoffs and total handoffs. last_last_time, last_time
are the tokens where the last and the time before last network handoff occurred. */
calculate $W^U$, $W^S$;   // $W^U$, $W^S$ are the final user-specified and service-determined weights
for i = 1:100   // 100 network selections for a MMT
  randomly get M, and calculate $W^O$;   // M is the network attribute matrix, $W^O$ is the
  // objective weights calculated by Entropy
  W = $\alpha * W^U + \beta * W^O + \gamma * W^S$;   // W is the final comprehensive weights
  calculate U, D; // U is the comprehensive utility matrix, D is the weighted decision matrix
  S = TOPSIS(D);   // S is the scores of the candidate networks calculated by TOPSIS
  bestID = highest(S);   // bestID is the ID of the network with the highest score in S
  if (i==1) {   // This is the first network selection
    old_old_ID = old_ID; old_ID = bestID; last_last_time=last_time; last_time = i;
  }
  else{
    if ((old_ID == bestID) || (old_ID != bestID && S[bestID]/S[old_ID] <= δ))
    // The current connected network is the best network, or does not meet the handover conditions
      bestID = old_ID;
    else{ // Meet the handover conditions
      if(old_old_ID != 0 && old_old_ID == bestID && last_last_time - last_time ==2)
      // The last connected network is the same as the best network selected this time.
        Unnecessary_count = Unnecessary _count +1;
      Total_count = Total_count+1; old_old_ID = old_ID; old_ID = bestID;
      last_last_time = last_time; last_time = i;
    }
  }
end for
```

FIGURE 14. Pseudo code to calculate the number of unnecessary handoff of our algorithm.

100 network selections of a MMT. The pseudo code of our algorithm for calculating the number of unnecessary handoff is described in Fig. 14. The results are shown in Fig. 15. And the simulation results are as follows:

- Our algorithm has the lowest percentage of unnecessary handoff, which is 3.1%.
- Fuzzy MCGDM has the highest unnecessary handoff probability.

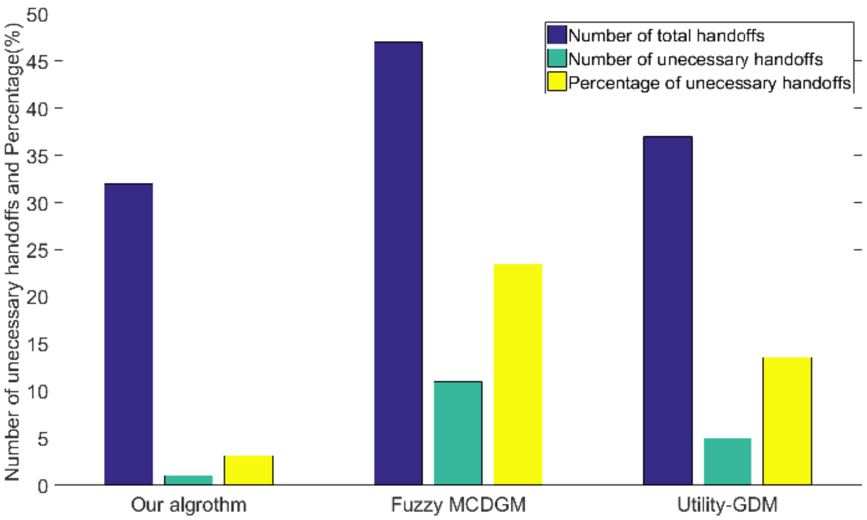


FIGURE 15. Numbers and percentage of unnecessary handoffs.

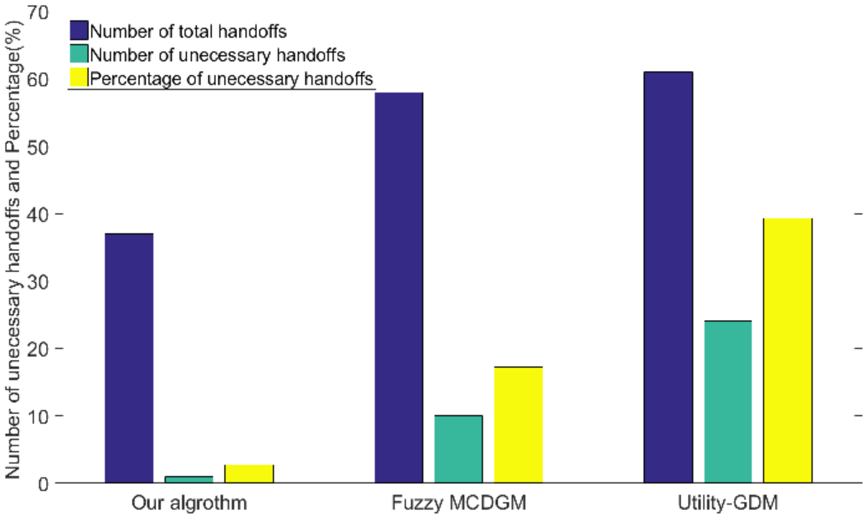


FIGURE 16. Numbers and percentage of unnecessary handoffs adding a new UMTS network.

- The unnecessary handoff probabilities of Fuzzy MCDGM and Utility-GDM are 23.4%, 13.5%, respectively.

Compared with Fuzzy MCGDM and Utility_GDM, the probability of unnecessary vertical handoffs of our algorithm decreased by 20.1 and 10.4 percentage respectively. Our algorithm shows better performance in reducing the number of unnecessary vertical handoffs, which can effectively reduce the ping-pong effect, improve the end user experience, and reduce the waste of resources.

If we add a new UMTS network, the ranges of its attributes are the same as that of the UMTS network's in Table. 5. We compare the unnecessary handoff probabilities of 100 network selections for a MMT of the three algorithms under the same conditions as above, and the results are shown in Fig. 16. By comparing Fig. 16 with Fig. 15, we can see that:

- Our algorithm has almost the same result under two experiments. The unnecessary handoff probability is 2.7%.
- Utility_GDM has the highest unnecessary handoff probability.
- The unnecessary handoff probabilities of Fuzzy MCDGM and Utility-GDM are 17.2%, 39.3%, respectively.

This is because Utility_GDM prefers the UMTS network. When we add a new UMTS network, the UMST algorithm will oscillate between the two networks, thus greatly increases the number of unnecessary handoffs. Therefore, by adding a new network, we can prove that our algorithm has good stability compared to the other two algorithms, thereby obtains a more stable network connection and improves the user experience.

V. CONCLUSIONS

This paper proposes a comprehensive MMT network selection algorithm. The algorithm considers three factors including user preferences, service characteristics and requirements and network attributes, and combines FAHP, TOPSIS, Entropy and utility function technologies to select the most appropriate network. The decision-making matrix is constructed by synthesizing the comprehensive weights and utility values of the network attributes for multiple services. The proportion of weights of the three factors can be adjusted by the correlation coefficient. The most appropriate network is selected according to the networks' score, which is obtained by TOPSIS, and threshold δ. The threshold value δ is used to determine whether the MMT maintains the current connection or handover to the optimal network. From the simulation results we can see that our algorithm satisfies the service's requirements and improves the user's satisfaction, and obtains relatively accurate network to access. Compared with the existing two MMT network selection algorithms, our algorithm obtains better gain, reduces the number of vertical handovers and avoid unnecessary handover to a certain extent, thereby reducing the ping-pong effect and obtaining a relatively stable network connection, proving that our algorithm has obvious advantages.

At the same time, this paper has some limitations. The parameters used in this paper (i.e., α, β, γ and δ) are static and determined through many experiments, which are not necessarily optimal. On the other hand, we only consider the network selection of a single MMT, without considering the load balance between multiple users and the MMT's state such as power consumption and the moving speed.

In future works, efforts will be concentrated on the dynamics of the parameters, so that the parameters can be adjusted dynamically and autonomously according to the running application and the actual network environment. In order to obtain complete VHO algorithm, handover triggering will be also considered. In addition, we should also consider the load balancing of multiple MMTs, as well as the state of MMT, such as speed and energy.

REFERENCES

[1] E. Falowo and H. A. Chan, "Dynamic RAT selection for multiple calls in heterogeneous wireless networks using group decision-making technique," *Comput. Netw.*, vol. 56, no. 4, pp. 1390–1401, 2012.

[2] O. E. Falowo and O. A. Taiwo, "Network selection decisions for multiple calls based on consensus level," *J. Netw. Syst. Manage.*, vol. 26, no. 3, pp. 592–615, 2018.

[3] E. Falowo and H. A. Chan, "Multiple-call handover decisions using fuzzy MCGDM in heterogeneous wireless networks," in *Proc. MILITARY Commun. Conf. (MILCOM)*, Baltimore, MD, USA, Nov. 2011, pp. 1909–1914.

[4] E. Falowo and H. A. Chan, "Effect of call dynamics of a multiservice multimode terminal on rat selection in heterogeneous wireless networks," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Anaheim, CA, USA, Dec. 2012, pp. 5249–5253.

[5] A. Taiwo and O. E. Falowo, "Comparative analysis of algorithms for making multiple-sessions handover decisions in next generation wireless networks," in *Proc. AFRICON*, Sep. 2013, pp. 1–6.

[6] E. Gustafsson and A. Jonsson, "Always best connected," *IEEE Wireless Commun.*, vol. 10, no. 1, pp. 49–55, Feb. 2003.

[7] M. Kassar, B. Kervella, and G. Pujolle, "An overview of vertical handover decision strategies in heterogeneous wireless networks," *Comput. Commun.*, vol. 31, no. 10, pp. 2607–2620, Jun. 2008.

[8] K. Ahuja, B. Singh, and R. Khanna, "Network selection in wireless heterogeneous environment by CPF hybrid algorithm," *Wireless Pers. Commun.*, vol. 98, no. 3, pp. 2733–2751, 2018.

[9] W. Shen and Q.-A. Zeng, "Cost-function-based network selection strategy in integrated wireless and mobile networks," *IEEE Trans. Veh. Technol.*, vol. 57, no. 6, pp. 3778–3788, Nov. 2008.

[10] H. AINashwan and A. Agarwal, "User-centric network selection in wireless heterogeneous networks," in *Proc. IEEE 30th Can. Conf. Elect. Comput. Eng. (CCECE)*, Windsor, ON, Canada, Apr. 2017, pp. 1–6.

[11] Z. Du, Q. Wu, P. Yang, Y. Xu, and Y.-D. Yao, "User-demand-aware wireless network selection: A localized cooperation approach," *IEEE Trans. Veh. Technol.*, vol. 63, no. 9, pp. 4492–4507, Nov. 2014.

[12] J. Chen, Y. Wang, Y. Li, and E. Wang, "QoE-aware intelligent vertical handoff scheme over heterogeneous wireless access networks," *IEEE Access*, vol. 6, pp. 38285–38293, 2018.

[13] N. U. Hasan, W. Ejaz, N. Ejaz, H. S. Kim, A. Anpalagan, and M. Jo, "Network selection and channel allocation for spectrum sharing in 5G heterogeneous networks," *IEEE Access*, vol. 4, pp. 980–992, 2016.

[14] S. Barmpounakis, A. Kaloxylos, P. Spapis, and N. Alonistioti, "Context-aware, user-driven, network-controlled RAT selection for 5G networks," *Comput. Netw.*, vol. 113, pp. 124–147, Feb. 2017.

[15] T. L. Saaty, "How to make a decision: The analytic hierarchy process," *Eur. J. Oper. Res.*, vol. 48, no. 1, pp. 9–26, Sep. 1990.

[16] M. Drissi, M. Oumsis, and D. Aboutajdine, "A multi-criteria decision framework for network selection over LTE and WLAN," *Eng. Appl. Artif. Intell.*, vol. 66, pp. 113–127, Nov. 2017.

[17] K. Ahuja, B. Singh, and R. Khanna, "Network selection based on weight estimation of QoS parameters in heterogeneous wireless multimedia networks," *Wireless Pers. Commun.*, vol. 77, no. 4, pp. 3027–3040, 2014.

[18] B. Roy, "The outranking approach and the foundations of ELECTRE methods," in *Readings in Multiple Criteria Decision Aid*. Berlin, Germany: Springer, 1990, pp. 155–183. doi: 10.1007/978-3-642-75935-2_8.

[19] J. M. Marquez-Barja *et al.*, "Breaking the vehicular wireless communications barriers: Vertical handover techniques for heterogeneous networks," *IEEE Trans. Veh. Technol.*, vol. 64, no. 12, pp. 5878–5890, Dec. 2015.

[20] U. Paul and O. E. Falowo, "Efficient RAT-selection for group calls using intuitionistic fuzzy TOPSIS in heterogeneous wireless networks," in *Proc. IEEE AFRICON*, Cape Town, South Africa, Sep. 2017, pp. 365–370.

[21] R. Luo, S. Zhao, and Q. Zhu, "Network selection algorithm based on group decision making for heterogeneous wireless networks," in *Proc. IEEE 9th Int. Conf. Commun. Softw. Netw. (ICCSN)*, Guangzhou, China, May 2017, pp. 397–402.

[22] E. Obayiuwana and O. Falowo, "A new network selection algorithm for group calls over heterogeneous wireless networks with dynamic multi-criteria," in *Proc. 13th IEEE Annu., Consum. Commun. Netw. Conf. (CCNC)*, Las Vegas, NV, USA, Jan. 2016, pp. 491–494.

[23] P. J. M. van Laarhoven and W. Pedrycz, "A fuzzy extension of Saaty's priority theory," *Fuzzy Set Syst.*, vol. 11, nos. 1–3, pp. 229–241, 1983.

[24] Q. Nguyen-Vuong, Y. Ghamri-Doudane, and N. Agoulmine, "On utility models for access network selection in wireless heterogeneous networks," in *Proc. IEEE Netw. Oper. Manage. Symp. (NOMS)*, Salvador, Bahia, Apr. 2008, pp. 144–151.

[25] I. Chamodrakas and D. Martakos, "A utility-based fuzzy TOPSIS method for energy efficient network selection in heterogeneous wireless networks," *Appl. Soft Comput.*, vol. 12, no. 7, pp. 1929–1938, 2012.

[26] R. K. Goyal, S. Kaushal, and A. K. Sangaiah, "The utility based non-linear fuzzy AHP optimization model for network selection in heterogeneous wireless networks," *Appl. Soft Comput.*, vol. 67, pp. 800–811, Jun. 2018.

[27] G. Liang and H. W. Yu, "Network selection algorithm for heterogeneous wireless networks based on service characteristics and user preferences," *EURASIP J. Wireless Commun.*, vol. 2018, no. 1, p. 241, Oct. 2018.

[28] C.-L. Hwang and K. Yoon, "Methods for multiple attribute decision making," in *Multiple Attribute Decision Making* (Lecture Notes in Economics and Mathematical Systems), vol. 186. Berlin, Germany: Springer-Verlag, 1981. doi: 10.1007/978-3-642-48318-9_3.

HEWEI YU was born in Shaanxi, China, in 1967. He received the B.S. and M.S. degrees in radio technique from Xi'an Jiaotong University, in 1989 and 1992, respectively, and the Ph.D. degree in circuits and systems from the South China University of Technology, in 2004, where he was an Engineer with the Research Institute of Computer Application, from 1992 to 2005.

Since 2010, he has been a Professor with the Computer Science and Engineering School, South China University of Technology. He has authored one book and more than 70 articles. His research interest includes wireless network access selection and fast handover techniques of mobile IPv6.

Dr. Yu was a recipient of the Seventh Education Achievement Award from Guangdong Province, in 2014.

YANAN MA was born in Henan, China, in 1995. She received the B.S. degree in computer science and technology from Anhui University, in 2017. She is currently pursuing the M.S. degree in computer science and engineering with the South China University of Technology, China.

JINGXI YU was born in Guangzhou, China, in 1998. He is currently pursuing the B.S. degree in mathematics with the University of Washington, USA.