Quality-of-experience-oriented network selection for indoor VLC heterogeneous networks

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***Abstract*—In this paper, we propose a novel network selection method oriented to users' quality-of-experience (QoE) for indoor visible light communication (VLC) heterogeneous networks. The proposed method considers the difference between user requirements for different parameters and the actual performance of each candidate network in these reference indicators. To improve QoE, a new indicator named "benefit-cost-ratio (BCR)" is defined to represent the user demand under different businesses and assist in sorting alternatives to select the optimal network for access. Simulation results show that through the proposed network selection scheme, the candidate networks could be effectively ranked and adjusted according to user requirements.**

***Index Terms*—VLC heterogeneous network, network selection, quality-of-experience**

I. Introduction

Recently, almost 80 percent of data traffic occurs indoors [1]. And radio frequency (RF) communication confronts with a tremendously growing demand for data services from indoor users. As one of the most promising technologies for the next generation wireless communication system, visible light communication (VLC) has attracted much more attention around the world due to its dual functionalities including illumination and high transmission rate. However, it is reasonable to consider the cooperation of VLC and other wireless networks to construct a more robust heterogeneous communication system for providing higher throughput and ubiquitous connections as a result of the limited coverage of VLC. In [2], a hybrid network model including VLC for downlink transmission and orthogonal frequency-division multiplexing access (OFDMA) for uplinks or downlinks only without VLC hotspots coverage was proposed. Authors in [3] investigated an on-line two-timescale resource optimization for heterogeneous VLC/RF networks by employing the Lyapunov optimization method. In [4], the authors formulated a load balancing problem for an indoor Wi-Fi/VLC hybrid network and proposed an algorithm in consideration of both user mobility and light-path blockage.

Users are usually covered by multiple networks in an indoor heterogeneous network. When they enter the room within range of the networks for the first time or switch networks according to different services, it is a critical decision to sort candidates and select the optimal network based on different attributes, e.g. rate, delay, and price. Multi-attributes-decision-making (MADM) is a decision making process by evaluating multiple attributes, and it aims to choose the best alternative among multiple alternatives. And there are some MADM based network selection methods. In [5], the network selection method used the analytic hierarchy process (AHP) to determine the importance of the attributes and the technique for order of preference by similarity to ideal solution (TOPSIS) to obtain the final network ranking. In [6], AHP with grey relational analysis technique and entropy technique for dynamic link selection in traffic offload scenarios were compared. Nevertheless, the methods only using AHP to determine weights have strong subjectivity and fail to consider network performance. On the other side, all of the candidates are just ranked based on the system input in TOPSIS in which user requirements are not considered effectively .

Furthermore, network services also attach great importance to providing users with good quality-of-experience (QoE). [7], [8] focused on resource allocation schemes in terms of QoE optimization. In [7], the authors discussed the QoE cycle and its implications toward QoE-aware traffic management. A random neural network based QoE estimation was proposed in [8]. However, few articles consider QoE in network selection.

Motivated by previous observations, we construct a heterogeneous network model combined with VLC, WiFi, and infrared (IR). In the hybrid system, we propose an optimal network selection method which could be divided into two steps, including weight calculation and network selection. The weight value represents the importance of a certain network performance parameter, and the network with the highest score is regarded as the optimal network that the user would choose to access. The main contributions of this paper are summarized as follows.

First, we establish a consistency optimization problem that considers four performance parameters at the same time in a VLC-based heterogeneous network, where AHP and the standard deviation method are utilized to calculate the values of the user's subjective weights and network's objective weights, respectively. And then, a mathematical model aiming at minimizing the difference between the subjective and objective results is constructed in order to obtain the comprehensive weight value corresponding to each attribute.

Second, we develop an efficient network selection algorithm to help users select the most suitable one from multiple hybrid networks for access, and define a new parameter called benefit-

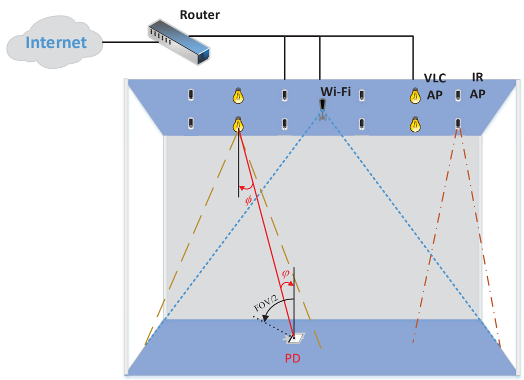

Fig. 1. The heterogeneous network system model.

cost-ratio (BCR) to evaluate the user's attitude towards benefit parameters such as achievable rate and cost parameters such as bandwidth or delay in order to understand the user's demand for QoE adequately. A larger BCR means higher cost-effective service requirements, which indicates that it is greatly expected to experience the best network performance at a limited cost from the user's perspective. Otherwise, it is considered that users would pursue high-performance service regardless of cost when BCR is extremely low. Therefore, BCR represents the QoE level expected by users under different business requirements, which could be a significant benchmark for supporting users to judge the best candidate network in the proposed network selection method.

The remainder of this paper is organized as follows. Section II presents the system model and calculation of weights. Section III introduces the QoE oriented selection method. Results and discussions are presented in Section IV. Finally, conclusions are drawn in Section V.

II. System Model and Weight Calculation

A. System Model

As shown in Fig. 1, we consider a heterogeneous network composed of a single Wi-Fi access point (AP), N VLC APs, and M IR APs.

Due to the high demand for the illumination intensity while transmitting data in VLC, the LED power is much larger than Wi-Fi power or IR power. However, the optical signal power is only a small fraction of the LED power, and the signal power is much important for calculating the transmission rate. Therefore, the transmission rate provided by VLC is given as follows. First of all, a VLC channel consists of the line of sight (LOS) and non-line of sight(NLOS) paths. The LOS gain is expressed as [9]:

$$H_{LOS} = \begin{cases} \frac{(m+1)}{2\pi d^2} A_{PD} \cos^m(\phi) \\ \times T(\varphi) g(\varphi) \cos(\varphi), \text{if } |\varphi| \leq \varphi_{FOV} \\ \\ 0, \qquad\qquad \text{if } |\varphi| \geq \varphi_{FOV} \end{cases} \tag{1}$$

where d denotes the distance between the LED and the user, A_{PD} denotes the physical area of the photodetector (PD), respectively. ϕ is the angle of irradiance φ is the angle of incidence, $T(\varphi)$ is the optical filter gain, $g(\varphi)$ is the optical concentrator gain, φ_{FOV} is the field of view (FOV) of the PD. m is the order of the Lambertian emission depending on the semi-angle φ_{semi} of the LED transmitter at half power which is given by $m = -In(2)/In(\cos(\varphi_{semi}))$.

Besides, the power received by the NLOS path is much less than that of LOS path [10]. Hence, only the LOS path gain is considered and the signal to noise ratio (SNR) is given as:

$$\xi = \frac{I_{elec}}{N_{vlc} B_{vlc}} = \frac{(R_{PD} H_{LOS} P_{opt}/\zeta)^2}{N_{vlc} B_{vlc}} \tag{2}$$

where I_{elec} is the signal obtained by PD, R_{PD} is the detector responsivity, P_{opt} is the transmitted optical power, ζ is the ratio of the transmitted optical power to the optical signal power. N_{vlc} and B_{vlc} denote the power spectral density of noise and the system bandwidth, respectively. The achievable rate of the user is computed by [11]:

$$r = \frac{B_{vlc}}{2} \log_2 \left(1 + \frac{e}{2\pi} \xi\right) \tag{3}$$

B. Weight Calculation

In this part, we calculate the weight to quantify the importance of attributes. n denotes the number of attributes, m denotes the number of networks. AHP is used to obtain subjective weights by inputting the judgement matrix [12]:

Step 1: Determination of the relative importance of the attributes

Attributes are compared pairwise according to their levels of importance concerning the scale shown in Table. I. The results are presented in a normalized judgement matrix $X = [x_{ij}]_{n \times n}$ Where $x_{ii} = 1, x_{ij} = 1/x_{ji}, x_{ij} \neq 0$, and x_{ij} is the importance of attribute i relative to attribute j.

Step 2: Calculate the subjective weight

The subjective weight $w_j^{'}$ of the attribute j is calculated by finding the eigenvector w^0 corresponding to the largest eigenvalue λ_{max} of the matrix X:

$$Xw^0 = \lambda_{max} w^0 \tag{4}$$

$$w_j^{'} = \frac{w_j^0}{\sum_{j=1}^{n} w_j^0} \tag{5}$$

To avoid potential inconsistency, the consistency ratio $CR = CI/RI$ is introduced with the consistency index

TABLE I
Saaty's Scale of Pairwise Comparison

Saaty's Scale	Relative importance of two elements
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2,4,6,8	Intermediate value

$CI = (\lambda_{\max} - n)/(n-1)$ and the random index (RI). While the value of RI is 0.90 when we consider four attributes. If CR is less than 10%, the inconsistency is acceptable. Then, we use the standard deviation method to obtain objective weights:

Step 1: Construct the attribute matrix

Based on the performance of networks, we construct an attribute matrix $S = [s_{ij}]_{m\times n}$, where s_{ij} is the value of the attribute j in the network i. And S is normalized by:

$$r_{ij} = \frac{s_{ij}}{\sqrt{\sum_{i=1}^{m} {s_{ij}}^2}}, i = 1, ..., m; j = 1, ..., n \tag{6}$$

Step 2: Calculate the objective weight

The objective weight $w_j^{''}$ of attribute j can be expressed as:

$$w_j^{''} = \frac{\sqrt{\sum_{i=1}^{m}\left(r_{ij} - \frac{1}{m}\sum_{i=1}^{m} r_{ij}\right)^2}}{\sum_{j=1}^{n}\sqrt{\sum_{i=1}^{m}\left(r_{ij} - \frac{1}{m}\sum_{i=1}^{m} r_{ij}\right)^2}} \tag{7}$$

After the subjective weights and objective weights are calculated, it is not feasible to add them directly. Thus, we assign the respective coefficients α, β to get a reasonable comprehensive weight ω for each attribute. We aim to maximize the consistency between the objective results and subjective results, and α and β could be calculated and obtained by:

$$\begin{cases} \min \mathrm{F} = \sum_{i=1}^{m}\left\{ \left(\sum_{j=1}^{n} \alpha r_{ij} {w_j}' - \sum_{j=1}^{n} \beta r_{ij} {w_j}''\right)^2 \right\} \\ s.t. \alpha + \beta = 1, 0 \le \alpha \le 1, 0 \le \beta \le 1 \end{cases} \tag{8}$$

$$\alpha = \frac{\sum_{i=1}^{m}\left[\left(\sum_{j=1}^{n} r_{ij} w_j^{''}\right)\left(\sum_{j=1}^{n}\left(r_{ij}\left(w_j^{''} + w_j^{'}\right)\right)\right)\right]}{\sum_{i=1}^{m}\left(\sum_{j=1}^{n} r_{ij} w_j^{'} + \sum_{j=1}^{n} r_{ij} w_j^{''}\right)^2} \tag{9}$$

$$\beta = \frac{\sum_{i=1}^{m}\left[\left(\sum_{j=1}^{n} r_{ij} w_j^{'}\right)\left(\sum_{j=1}^{n}\left(r_{ij}\left(w_j^{''} + w_j^{'}\right)\right)\right)\right]}{\sum_{i=1}^{m}\left(\sum_{j=1}^{n} r_{ij} w_j^{'} + \sum_{j=1}^{n} r_{ij} w_j^{''}\right)^2} \tag{10}$$

Then, the comprehensive weight w_j of attribute j is written as:

$$w_j = \alpha {w_j}' + \beta {w_j}'' \tag{11}$$

III. QoE-oriented network selection method

A. TOPSIS

TOPSIS is based on the idea of selecting the alternative with the shortest distance from the positive solution A^+ and the greatest distance from the negative solution A^- [5]. Moreover, the attributes are divided into benefit attributes J_1 and cost attributes J_2:

Step 1: Construct normalized matrix

The attribute matrix is shown as $S = [s_{ij}]_{m\times n}$ in section II.B, and is normalized from (6):

Step 2: Construct the weighted matrix

$$v_{ij} = w_j \times r_{ij}, i = 1, ..., m; j = 1, ...n \tag{12}$$

Where w_j denotes the comprehensive weight of attribute j.

Step 3: Determine the positive solution and negative solution

$$\begin{aligned} A^+ &= \left\{a_1^+, a_2^+, ..., a_j^+, ..., a_n^+\right\} \\ &= \left\{\left(\max_i v_{ij} \,|j \in J_1\right), \left(\min_i v_{ij} \,|j \in J_2\right) |i = 1, ..., m\right\} \end{aligned} \tag{13}$$

$$\begin{aligned} A^- &= \left\{a_1^-, a_2^-, ..., a_j^-, ..., a_n^-\right\} \\ &= \left\{\left(\min_i v_{ij} \,|j \in J_1\right), \left(\max_i v_{ij} \,|j \in J_2\right) |i = 1, ..., m\right\} \end{aligned} \tag{14}$$

Step 4: Calculate the Euclidean distances from the candidate to the positive solution and negative solution

$$ {D_i}^+ = \sqrt{\sum_{j=1}^{n}\left(v_{ij} - a_j^+\right)^2}, i = 1, ..., m \tag{15}$$

$$ {D_i}^- = \sqrt{\sum_{j=1}^{n}\left(v_{ij} - a_j^-\right)^2}, i = 1, ..., m \tag{16}$$

Step 5: Calculate relative closeness to the ideal solution

$$C_i = \frac{D_i^-}{D_i^- + D_i^+}, i = 1, ..., m \tag{17}$$

Step 6: Rank the alternatives according to the decreasing order of C_i.

Practically, we regard user experience as an important issue for network selection, which is not considered in TOPSIS. TOPSIS might select the network with the best performance that the user does not need. In other words, the best network is the one that could meet user requirements. Therefore, we define a novel parameter to quantify user requirements and design a QoE oriented network selection method.

B. The definition of BCR

We hope to find out more hidden information to improve user experience. Besides choosing the network with better performance, which can be regarded as maximizing the users' benefit, we consider user attitude toward cost as an important issue. Hence, a new parameter named BCR is defined, which describes the relationship between benefit and cost more deeply. A larger BCR means higher cost-effective service requirements, which indicates that it is greatly expected to experience the best network performance at a limited cost from the user's perspective. Otherwise, it is considered that

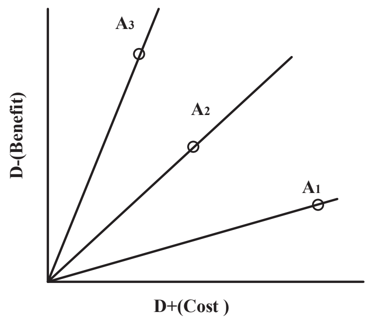

Fig. 2. The rank by TOPSIS.

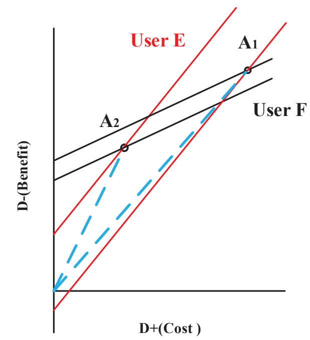

Fig. 3. The rank by the proposed method and TOPSIS.

users would pursue high-performance service regardless of cost when BCR is extremely low. BCR is expressed as:

$$BCR = \mu = \frac{\sum_{j=1}^{N_{J_1}} w_j}{\sum_{i=1}^{N_{J_2}} w_i} \tag{18}$$

where N_{J_1} and N_{J_2} denote the number of elements in J_1 and J_2, respectively.

C. Network selection method

In TOPSIS, (17) is used to sort which is proportional to $C_i^* = D_i^- / D_i^+$. It can be transformed into a linear function:

$$D^- = C_i^* D^+ \tag{19}$$

Here, C_i^* denotes the slope of the function, and the y-axis intercept is zero as shown in Fig. 2. The best candidate A3 is the one with the steepest slope where C_i^* gets maximum value.

It is worth mentioning that D^- is regarded as the benefit of being far from the negative solution, D^+ is regarded as the cost of being far from the positive solution. Furthermore, the slope is a special parameter that represents the relative changing rate of the benefit and the cost. In other words, the slope can be variable according to the different requirements of users. Hence, we give a new practical meaning to the slope by replacing it with BCR. As shown in Algorithm 1, the QoE-oriented network selection method is proposed. And the linear function is redesigned as:

$$D^- = \mu D^+ + \delta \tag{20}$$

where δ is the score of each candidate. χ is the optimal network with the highest score:

$$\chi = \arg\max_i (\delta_i) \tag{21}$$

where δ_i is the score of the candidate i. As shown in Fig. 3, red lines and black lines represent the selection of two users, E and F, respectively. For user E with a larger μ, it is indicated that he pursues higher cost-effectiveness, so A2 is preferred. On the contrary, user F has a lower μ, which shows A1 with the best performance is preferred. Additionally, if they apply TOPSIS to make a selection as shown in the blue dotted line, both of them would select A2 because it has a larger slope. Therefore, the proposed method mines another preference information of users. The information leads to a change in the result of selection. We believe the change will better match the requirements of users and improve their experiences.

Algorithm 1: QoE-oriented Network Selection

Input : n, the number of the attributes; ω_j, the comprehensive weight of attribute j; $S = [s_{ij}]_{m \times n}$, s_{ij} is the value of the attribute i in the network j.

Output: χ, the optimal network.

Initialization: J_1, the benefit attributes set; J_2, the cost attributes set; μ, the user BCR ;
for $j \in n$ **do**
  for $i \in m$ **do**
    Calculate normalized matrix r_{ij} using Eq. (6)
  Calculate weighted matrix v_{ij}: $v_{ij} = w_j \times r_{ij}$
for $j \in n$ **do**
  Calculate the positive solution and the negative solution :
  if $j \in J_1$ **then**
    $a_i^+ = \arg\max_i(v_{ij})$; $a_i^- = \arg\min_i(v_{ij})$;
  else
    $a_i^+ = \arg\min_i(v_{ij})$; $a_i^- = \arg\max_i(v_{ij})$;
for *each* $i \in m$ **do**
  Calculate the Euclidean distances using ${D_i}^+$ and ${D_i}^-$ using Eqs. (15) (16) ;
  Calculate the score $\delta_i = D_i^- - \mu D_i^+$
$\chi = \arg\max_i(\delta_i)$;

IV. Simulation Results

We consider an indoor 5m*5m*3m square room with 3 available networks (i.e., VLC, IR, and Wi-Fi), 3 services (i.e., conversation, video stream, and background services) and 4 attributes (i.e., rate, BER, delay, and price). Rate is the benefit attribute. BER, delay, and price are the cost attributes. The

TABLE II
PARAMETERS OF ALTERNATIVE NETWORKS

Parameter	Wi-Fi	IR	VLC
Rate	6Mbps	4Mbps	80Mbps
BER	4×10^{-6}	2×10^{-6}	9×10^{-6}
Delay	60ms	150ms	40ms
Price	0.6	0.2	0.1

TABLE III
THE JUDGEMENT MATRIX OF CONVERSATIONAL SERVICE

	Delay	BER	Rate	Price
Delay	1	3	9	6
BER	1/3	1	7	5
Rate	1/9	1/7	1	4
Price	1/6	1/5	1/4	1

rate, BER, and average delay refer to the achievable rate of the system, the probability of errors in transmission, and the total delay of propagation and signal processing, respectively. And the price indicates the normalized cost of system construction. All of the above parameters are greatly crucial in communication. Other basic parameters are summarized as $A_{PD} = 0.01m^2$, $T(\varphi) = 1$, $g(\varphi) = 1$, $\varphi_{FOV} = 70^0$, $\varphi_{semi} = 60^0$, $R_{PD} = 0.55A/W$, $P_{opt} = 3W$, $\zeta = 3$, $N_{vlc} = 10^{-21}A^2/Hz$, $B_{vlc} = 20MHz$. The rate of VLC is calculated based on (3), and other attributes are listed in Table. II [13]–[15]. Moreover, judgement matrices for AHP are given in Table. III-V.

In Fig. 4, we compare subjective weights, objective weights, and comprehensive weights under conversation service. It is straightforward to see that users have high requirements for delay and BER. For objective weights, there is a large difference between the three networks in rate, so it has maximum weight. However, the demand for rate is loose when users have conversations, so the comprehensive weight of the rate is small.

Figures 5 and 6 present three types of weights under video stream and background services. When watching videos, users

TABLE IV
THE JUDGEMENT MATRIX OF VIDEO STREAM SERVICE

	Delay	BER	Rate	Price
Delay	1	1/9	1/5	1/3
BER	9	1	3	5
Rate	5	1/3	1	4
Price	3	1/5	1/4	1

TABLE V
THE JUDGEMENT MATRIX OF BACKGROUND SERVICE

	Delay	BER	Rate	Price
Delay	1	1/4	1/7	1/9
BER	4	1	1/6	1/7
Rate	7	6	1	1/3
Price	9	7	3	1

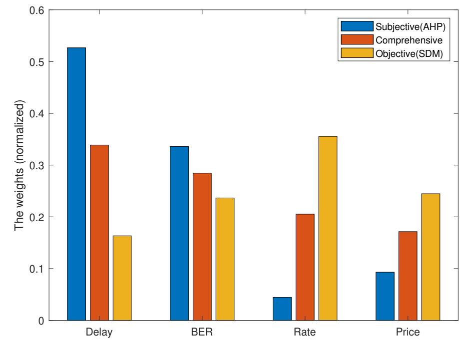

Fig. 4. The weights of conversation service.

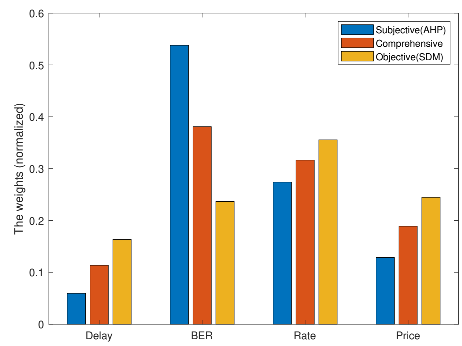

Fig. 5. The weights of video stream service.

usually put the demand of low BER as a priority. Meanwhile, delay and price are assigned lesser weights. Additionally, users usually prefer a high rate and low price service when they send emails or download data. Therefore, price and BER are assigned larger weights under background service.

In Table. VI, we compare the selection results of the proposed method with SAW, MEW, and TOPSIS. It is observed that SAW, MEW, and TOPSIS has the same rank under different services. They ignore the user preference and always select the network with the best performance. On the contrary, the proposed method adjusts the selection based on user service. Wi-Fi is preferred for conversation and video stream, and VLC is selected for background services because of its higher rate and lower price. Therefore, this method can improve QoE

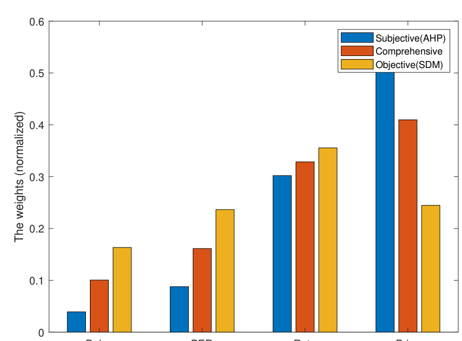

Fig. 6. The weights of background service.

TABLE VI
THE SELECTION RESULTS

	SAW			MEW			TOPSIS			Proposed method		
Networks	C	V	B	C	V	B	C	V	B	C	V	B
Wi-Fi	0.4461(2nd)	0.3969(2nd)	0.4991(2nd)	3.3840(1st)	3.5607(1st)	3.5972(1st)	0.4268(3rd)	0.3676(3rd)	0.1687(3rd)	-0.7869(1st)	-0.5247(1st)	-0.7755(3rd)
VLC	0.5923(1st)	0.7239(1st)	0.5657(1st)	3.3754(2nd)	3.0798(2nd)	3.5478(2nd)	0.5188(1st)	0.4762(1st)	0.4752(1st)	-1.0315(2nd)	-0.5320(2nd)	-0.4892(1st)
IR	0.4214(3rd)	0.2656(3rd)	0.3111(3rd)	2.5841(3rd)	2.7004(3rd)	2.6593(3rd)	0.4948(2nd)	0.4752(2nd)	0.4696(2nd)	-1.3244(3rd)	-0.6599(3rd)	-0.6638(2nd)

C, V, and B are conversation, video stream, and background services.

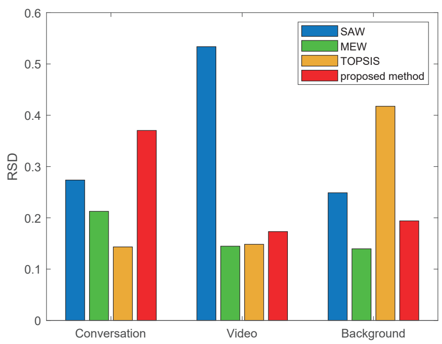

Fig. 7. The RSD of four methods.

and make reasonable usage for network resources. In Fig. 7, we examine the relative-standard-deviation (RSD) [16] which indicates the deviation of results from its mean value and is defined as $RSD = SD/\text{mean} \times 100\%$, where SD denotes the standard deviation. It can be seen that SAW and the proposed method have larger RSD, so the results are more dispersed and conducive for selection.

V. CONCLUSION

This paper investigates the optimal network selection problem based on user requirements in VLC-based heterogeneous communication systems. We propose a new concept named the "benefit-cost ratio (BCR)" to represent the requirements of users toward various services. And then a novel QoE-oriented network selection scheme that combines the subjective preference of users with the objective performance of three candidate networks including VLC, WiFi, and IR is put forward, in which a linear function based on BCR is also formulated to determine the network performance more accurately and help users to improve their QoE consequently. Simulation results demonstrate the feasibility of the proposed network selection method that could effectively adjust the priority of all candidate networks in real time according to different types of service.

VI. ACKNOWLEDGMENT

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