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An improved multilevel fuzzy comprehensive evaluation algorithm for security performance

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Abstract It is of great importance to take various factors into account when evaluating the network security performance. Multilevel fuzzy comprehensive evaluation is a relatively valid method. However, the traditional multilevel fuzzy comprehensive evaluation algorithm relies on the expert's knowledge and experiences excessively, and the result of the evaluation is usually less accurate. In this article, an improved multilevel fuzzy comprehensive evaluation algorithm, based on fuzzy sets core and entropy weight is presented. Furthermore, a multilevel fuzzy comprehensive evaluation model of P2P network security performance has also been designed, and the improved algorithm is used to make an instant computation based on the model. The advantages of the improved algorithm can be embodied in comparison with the traditional evaluation algorithm.

Keywords security, multilevel fuzzy comprehensive evaluation, entropy weight, P2P network

1 Introduction

A fuzzy comprehensive evaluation can do evaluation under various fuzzy circumstances. In a single-level fuzzy comprehensive evaluation, mistakes often occur when there are excessive evaluation factors. Meanwhile, the overabundant evaluation-set elements will result in difficulties in admeasuring the weights rationally. Therefore a multilevel fuzzy comprehensive evaluation is presented to solve these problems. However, because the traditional evaluation algorithm relies on the expert's knowledge and experiences excessively, the result of the evaluation is usually less accurate.

In this article, the mathematical definitions of the single-level fuzzy comprehensive evaluation and multilevel fuzzy comprehensive evaluation are introduced. An improved multilevel fuzzy comprehensive evaluation algorithm based on fuzzy sets core and entropy weight is presented. Also a multilevel fuzzy comprehensive evaluation model of P2P network security performance is designed to test the improved algorithm and the advantages of this improved algorithm are shown by comparing the evaluation result with that of the traditional evaluation algorithm.

2 Single-level fuzzy comprehensive evaluation

2.1 General process

Definition 1 Given two limited full sets $U = \{u_1, u_2, \ldots, u_m\}$ and $V = \{v_1, v_2, \ldots, v_n\}$, R is a fuzzy relation between U and V, $R = (r_{ij})_{m\times n}$, $0 \leqslant r_{ij} \leqslant 1$. If $A \subseteq U$ and $B \subseteq V$, there is a relation that is defined as follows:

$$B = A \circ R \tag{1}$$

where "$\circ$" represents the fuzzy operator. The relation is then called as fuzzy change [1], that is, change from the fuzzy sets on U to fuzzy sets on V.

Figure 1 depicts the general process of single-level fuzzy comprehensive evaluation.

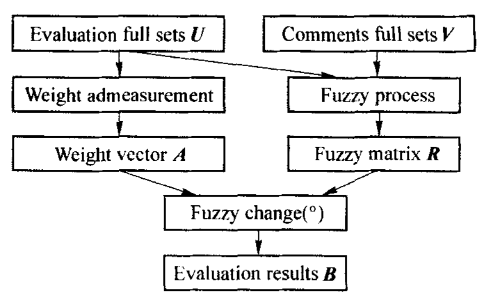

Fig. 1 General process of fuzzy comprehensive evaluation

2.2 Mathematical model

Definition 2 Let the set of m factors considered in evaluation be $U = \{u_1, u_2, \ldots, u_m\}$. Let the set of n comments be $V = \{v_1, v_2, \ldots, v_n\}$. With r_{ij} presenting the grade of membership of factor u_i aiming at comment v_j, the fuzzy relation between factor full sets and comment full sets can be described by the evaluation matrix R:

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$$\boldsymbol{R}=\begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{pmatrix} \tag{2}$$

where $0 \leqslant r_{ij} = \mu_R(u_i, v_j) \leqslant 1$, $i = 1, 2, \ldots, m$; $j = 1, 2, \ldots, n$.

Definition 3 The weight, that is, the extent of recognition of factors from valuators can be viewed as the fuzzy subset of factor full sets $\boldsymbol{U}$ when an object is evaluated roundly. Let $\boldsymbol{A} = (a_1, a_2, \ldots, a_m)$ be the symbol of weight, where $0 \leqslant a_i \leqslant 1$, $i = 1, 2, \ldots, m$. Let $\boldsymbol{B}$ as synthesized by $\boldsymbol{A}$ and $\boldsymbol{R}$ be the final evaluation of an object with many factors considered by the valuators. This process is called as fuzzy comprehensive evaluation, whose mathematical model is: $\boldsymbol{B} = \boldsymbol{A} \circ \boldsymbol{R} = (b_1, b_2, \ldots, b_n)$. Different definitions of fuzzy operator "$\circ$" will lead to different fuzzy comprehensive evaluation models. In this article, the M ($\bullet$, $\oplus$) model [2] is used to get the general computation formula of evaluation vectors:

$$B_j = \min\left(1, \sum_{i=1}^{m} a_i r_{ij}\right) \tag{3}$$

3 The algorithm of multilevel fuzzy comprehensive evaluation

In a single-level fuzzy comprehensive evaluation, if there are too many evaluation factors, every weight of the weight vector will be diminished. As a result, it will result in evaluation mistakes with difficulties in admeasuring the weights rationally. Therefore, a multilevel fuzzy comprehensive evaluation is needed when there are many evaluation factors.

3.1 General modality

For a given evaluation, if full set $\boldsymbol{U}$ is composed of k layers where $k \geqslant 2$, with the first layer (the topmost layer), including m factors that is $\boldsymbol{U} = (U_1^{(1)}, U_2^{(1)}, \ldots, U_m^{(1)})$ and $\boldsymbol{V} = (v_1, v_2, \ldots, v_n)$, the general modality of multilevel fuzzy comprehensive evaluation is (chosen here as $k = 3$)

$$\boldsymbol{B} = \boldsymbol{A} \circ \boldsymbol{R} = \boldsymbol{A} \circ \begin{pmatrix} \boldsymbol{A}_1 \circ \begin{pmatrix} \boldsymbol{A}_{11} \circ \boldsymbol{R}_{11} \\ \vdots \\ \boldsymbol{A}_{1p} \circ \boldsymbol{R}_{1p} \end{pmatrix} \\ \vdots \\ \boldsymbol{A}_m \circ \begin{pmatrix} \boldsymbol{A}_{m1} \circ \boldsymbol{R}_{m1} \\ \vdots \\ \boldsymbol{A}_{mq} \circ \boldsymbol{R}_{mq} \end{pmatrix} \end{pmatrix} \tag{4}$$

where $\boldsymbol{A}$ represents the weight vector of every layer, x which is the number of its subscript represents each weight vector of layer $x + 1$, and $\boldsymbol{R}$ represents the fuzzy relation matrix of the base layer (layer k).

The process of multilevel fuzzy comprehensive evaluation begins with the base layer (layer k), with a stepwise computation that is completed upwards, to the final evaluation set $\boldsymbol{B}$. The evaluation result of layer k is the very grade of membership of the factor of layer $k - 1$.

3.2 An improved multilevel fuzzy comprehensive evaluation algorithm

During the computation process of fuzzy comprehensive evaluation, the rational establishment of fuzzy relation of matrix $\boldsymbol{R}$ and the weight vector $\boldsymbol{A}$, has a great influence on the final evaluation result. The fuzzy relation attained from the method of expert evaluation and fuzzy statistics has the characteristics of subjectivity and deficiency. Similarly weight admeasurements with the method of expert consultation and evaluation (Delphi) [3] cannot satisfy the accuracy requirement. At present, the method of AHP [4–5] is often used in weight computation, which is just a more mathematical disposal of the expert's subjective estimation. Although it makes the evaluation more scientific, the deficiency of the expert's experience and knowledge still exists. Thereby this article focuses on the rational optimization of fuzzy relation matrix and the accurate admeasurements of weights. The method of fuzzy sets core [6] has been used here, to optimize the fuzzy relation matrix and that of entropy weight to establish weight vectors.

3.2.1 Optimization of fuzzy relation matrix

Definition 4 Let $\boldsymbol{U}$ be the limitary and measurable set of real number region $\boldsymbol{S}$. The core of membership function $\mu_D(x)$, which belongs to the fuzzy set $\boldsymbol{D}$ of $\boldsymbol{U}$ can be defined as:

$$G_D = \frac{\int_U \mu_D(x) x \mathrm{d}x}{\int_U \mu_D(x) \mathrm{d}x} \tag{5}$$

where $\int_U \mu_D(x)\mathrm{d}x \neq 0$. Especially when the full set $\boldsymbol{U} = \{x_1, x_2, \ldots, x_n\} \subset \boldsymbol{S}$ ($\boldsymbol{S}$ is a real number region), it becomes :

$$G_D = \frac{\sum_{i=1}^{n} \mu_D(x) x}{\sum_{i=1}^{n} \mu_D(x)} \tag{6}$$

where $\sum_{i=1}^{n} \mu_D(x) \neq 0$.

The core, as an inherent attribute of fuzzy set, depicts the place where the membership function of the fuzzy set concentrates together in the full set $\boldsymbol{U}$. Thereforethe core of the fuzzy set can be used to describe the admeasurements of the membership function. The method of comprehensive evaluation based on fuzzy set core can be used to optimize the fuzzy relation matrix, which can reflect the advantages and disadvantages of various factors objectively. This is because the larger the core is, the more praise comments its factor will gain; and the more praise comments it gains, the better the factor will be and vice versa.

3.2.2 The method of entropy weight

The idea of entropy comes from thermodynamics [7]. Introduced into informatics by Shannon, it is used as a measurement for uncertainty: the more the information, the less the uncertainty. Then the entropy will also be less and vice versa. Here entropy represents the uncertainty of factors that satisfy the comments. The adjustment of weights will be based on the membership function r_{ij} in this article.

Definition 5 Entropy of evaluation factors.

In the evaluation issue including m evaluation factors and n comments (it is called the (m, n) evaluation issue), the entropy of an evaluation factor i can be defined as:

$$H_i = -k\sum_{j=1}^{n} r_{ij}\ln r_{ij}, \quad i = 1, 2, \ldots, m \tag{7}$$

where $k = (\ln n)^{-1}$. It is assumed that when $r_{ij} = 0$, $r_{ij}\ln r_{ij} = 0$.

Definition 6 Entropy weight of evaluation factors.

In the (m, n) evaluation issue, the entropy weight of the evaluation factor i can be defined as:

$$\omega_i = \frac{1 - H_i}{m - \sum_{i=1}^{m} H_i} \tag{8}$$

where $0 \leqslant \omega_i \leqslant 1$, $\sum_{i=1}^{m}\omega_i = 1$.

4 Instance computation

Instant computation has been made based on the model of P2P network security. In P2P networks, nodes are logically symmetrical. Each node serves as both a server and a client. All nodes can communicate with each other directly. In this architecture, people can make full use of the idle computation resources and storage resources.

In P2P networks, because the nodes are dispersible and difficult to manage and control effectively, the security problem becomes more and more serious. Consequently, many evaluation factors have been considered from various aspects, and the multilevel fuzzy comprehensive evaluation model has been used to make an analysis of P2P network security in order to get an effective scheme.

4.1 Evaluation model

According to some references [8–17], many evaluation factors from various aspects are colligated and the evaluation model in Fig. 2 is constructed.

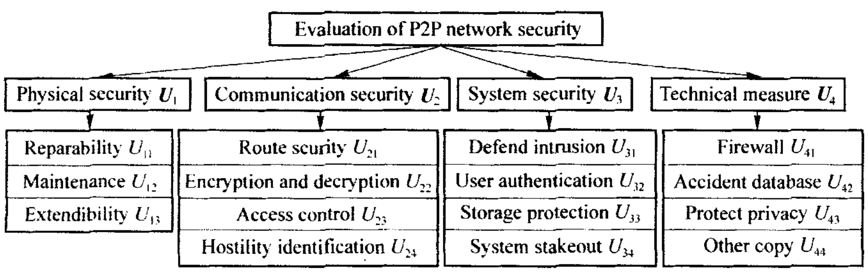

Fig. 2 The Evaluation model of P2P network security performance

4.2 Realization of the improved algorithm

As communication security is the most important in P2P network, the method of fuzzy comprehensive evaluation is used ($k = 2$ is chosen) to make an instant analysis of the communication security U_2, in the evaluation model. In this article, comment set V = {foolproof, more secure, unsecured, more dangerous, very dangerous} is chosen. According to the comment set V and some data, the method of fuzzy statistics and expert consultation is adopted to get the grade of membership of all factors aiming at comment set V.

4.2.1 Computation of the second layer (the base layer)

The fuzzy relation matrix of communication security U_2 aiming at comment set V in P2P network is:

$$\boldsymbol{R}_2 = \begin{pmatrix} 0.1 & 0.2 & 0.4 & 0.2 & 0.1 \\ 0.2 & 0.3 & 0.2 & 0.2 & 0.1 \\ 0.2 & 0.2 & 0.3 & 0.2 & 0.1 \\ 0.1 & 0.3 & 0.4 & 0.1 & 0.1 \end{pmatrix}$$

Numbers 1, 2, 3, 4, 5 are used to represent the comment set V, that is:

1—foolproof

2—more secure

3—unsecured

4—more dangerous

5—very dangerous

1) Using the method of fuzzy sets core to optimize fuzzy relation matrix.

According to Eq. (6) and fuzzy relation matrix $\boldsymbol{R}_2$, arrived at is:

$$G_{U_{21}} = \frac{0.1+0.2\times3+0.4\times5+0.2\times7+0.1\times9}{2\times(0.1+0.2+0.4+0.2+0.1)}=2.5$$

In the same way, what can be got is:

$$G_{U_{22}} = 2.2,\ G_{U_{23}} = 2.3,\ G_{U_{24}} = 2.3$$

Then the optimization matrix is derived

$$G_{U_2} = (2.5 \quad 2.2 \quad 2.3 \quad 2.3)^{\mathrm{T}}$$

2) Using the method of entropy weight to establish weight vectors

According to Eqs. (7) and (8), the method of entropy weight is used to compute the four factors of $\boldsymbol{U}_2$:

$$\omega_1 = 0.320,\ \omega_2 = 0.119,\ \omega_3 = 0.119,\ \omega_4 = 0.442$$

Then there is the weight vector

$$\boldsymbol{A}_2 = (0.320 \quad 0.119 \quad 0.119 \quad 0.442).$$

According to M (• , ⊕) model, the evaluation result of the first layer can be known:

$B_2 = \boldsymbol{A}_2 \circ G_{U_2} = (0.320\ 0.119\ 0.119\ 0.442) \circ$

$(2.5\ 2.2\ 2.3\ 2.3)^{\mathrm{T}} = 2.35$

Similarly, the evaluation results of the first layer can be calculated from $\boldsymbol{U}_1$, $\boldsymbol{U}_3$, $\boldsymbol{U}_4$

$$B_1 = 2.76,\ B_3 = 2.71,\ B_4 = 2.74.$$

4.2.2 Computation of the first layer (the topmost layer)

According to the expert's comments and the sample analysis, the fuzzy relation matrix of the four factors is obtained, aiming at comment set $\boldsymbol{V}$ in the P2P network security:

$$\boldsymbol{R} = \begin{pmatrix} 0.2 & 0.2 & 0.3 & 0.15 & 0.15 \\ 0.1 & 0.1 & 0.3 & 0.3 & 0.2 \\ 0.2 & 0.2 & 0.3 & 0.2 & 0.1 \\ 0.15 & 0.2 & 0.3 & 0.2 & 0.15 \end{pmatrix}$$

According to the fuzzy relation matrix $\boldsymbol{R}$, the entropy weight is used to establish the weight vector:

$$\boldsymbol{A}_1 = (0.156 \quad 0.461 \quad 0.227 \quad 0.156)$$

Then the fuzzy change is found for the second layer:

$B = \boldsymbol{A}_1 \circ \boldsymbol{G} = \boldsymbol{A}_1 \circ \ (B_1\ \ B_2\ \ B_3\ \ B_4)^{\mathrm{T}} =$

$(0.156\ 0.461\ 0.227\ 0.156) \circ (2.76\ 2.35\ 2.71\ 2.74)^{\mathrm{T}} =$

3.28

4.2.3 Disposal of the evaluation result

Because $B = 3.28$ is most close to 3, the comprehensive evaluation result aiming at P2P network security is 3—unsecured. Using the method of ration disposal, it is calculated as:

$$P_1 = (4 - 3.28)\times 100\% = 72.0\%$$

$$P_2 = (3.28 - 3)\times 100\% = 28.0\%$$

that is to say, the proportion of the unsecured is 72.0%, and that of the more dangerous is 28.0%.

5 Algorithm evaluation

5.1 Realization of the traditional algorithm

In the traditional evaluation algorithm, the method of AHP is mostly used to admeasure the weights of comment set factors. This article takes $\boldsymbol{U}_2$ as an example. Table 1 shows the estimate matrix $\boldsymbol{Q}_2$, which is constructed by using the method of expert evaluating on a scale of 1–9 to make a comparison among the four sub-factors of $\boldsymbol{U}_2$. The estimate matrices of other factors can be acquired in the same way.

Table 1 Estimate matrix $\boldsymbol{Q}_2$

Q_2	U_{21}	U_{22}	U_{23}	U_{24}
U_{21}	1	3	3	1/2
U_{22}	1/3	1	1	1/4
U_{23}	1/3	1	1	1/4
U_{24}	2	4	4	1

The estimate scale is defined in Table 2:

Table 2 Estimate scale

The scale	Definition
1	The two factors have an equivalence importance
3	One factor is little important than the other
5	One factor is obviously important than the other
7	One factor is mightily important than the other
9	One factor is extremely important than the other
2, 4, 6, 8	In the middle of the above neighbor factors

The value of weight vector $\boldsymbol{A}_2'$ of the four sub-factors of $\boldsymbol{U}_2$ from the method of AHP are (0.296 7, 0.109 4, 0.109 4, 0.484 5). According to the M (• , ⊕) model, the evaluation result of U_2 on the first layer can be found: $\boldsymbol{B}_2' = \boldsymbol{A}_2' \circ \boldsymbol{R}_2 = (0.12\ 0.26\ 0.37\ 0.15\ 0.1)$. Likewise, the final evaluation result will be:

$$\boldsymbol{B} = (0.16\ 0.23\ 0.27\ 0.22\ 0.13)$$

The method of centesimal score and ration disposal is used to make an adjustment on the final evaluation vector. They are marked as follows: $50 \leqslant c_1 < 60$ (foolproof), $60 \leqslant c_2 < 70$ (more secure), $70 \leqslant c_3 < 80$ (unsecured), $80 \leqslant c_4 < 90$ (more dangerous), $90 \leqslant c_5 \leqslant 100$ (very dangerous). As a result, there is a score vector $\boldsymbol{C} = (c_1 \ \ c_2 \ \ c_3 \ \ c_4 \ \ c_5)$ which is about comments. Because the score about comments is an interval, the following three representational scores are computed:

$$S_{\text{high}} = \frac{\sum_{i=1}^{n} b_i c_{\text{HIGH}i}}{\sum_{i=1}^{n} b_i} \tag{9}$$

$$S_{\text{low}} = \frac{\sum_{i=1}^{n} b_i C_{\text{LOW}i}}{\sum_{i=1}^{n} b_i} \tag{10}$$

$$S_{\text{middle}} = \frac{\sum_{i=1}^{n} b_i c_{\text{MIDDLE}i}}{\sum_{i=1}^{n} b_i} \tag{11}$$

where $c_{\text{HIGH}i}$ represents a comments score vector composed of upper limit of the region of each factor, $c_{\text{LOW}i}$ of lower limit, and $c_{\text{MIDDLE}i}$ of the middle value.

After the rational disposal of the final evaluation in P2P network security, the following is obtained:

$S_{\text{high}} = 79.22$, $S_{\text{middle}} = 75.05$, $S_{\text{low}} = 70.3$

After making adjustments on the comments with the rational disposal, the highest score $79.22 < 80$ and the lowest score $70.3 > 70$ are obtained. Therewith, the evaluation result of the P2P network security is three, which means the security standard is just "unsecured".

5.2 Comparison between the two algorithms

After making a comparison between the two algorithms, it is found that the results of the improved evaluation are in accord with the results of the traditional evaluation on the whole. It also reflects the actual security performance of P2P network. In the traditional fuzzy comprehensive evaluation algorithm, the method of AHP is mostly used to admeasure the weights of comment set factors. The estimate matrices are constructed only by experts, and the weight admeasurements rely on the expert's subjective evaluation excessively. When there are more factors, the extent of complication increases. As a result, the persuasion of this method of weight admeasurements decreases and the disadvantages of the algorithm emerge. In the improved fuzzy comprehensive evaluation algorithm, at first the method of fuzzy sets core is used to optimize the fuzzy relation matrix. It improves the capability of the algorithm. Then, the method of entropy weight is used to establish weight vectors. This makes the computation process fair and open. And thereby, the uncertainty of the evaluation result brought by the subjectivity can be avoided effectively and the evaluation result becomes more objective and more reasonable.

6 Conclusions

In this article, from the results of instant computation, it is found that the improved multilevel fuzzy comprehensive evaluation has a lower complication and a higher objectivity and accuracy. It can avoid many disadvantages that exist widely in the traditional algorithm. However, as the fuzzy relation matrices used in this article are established by some experts, the subjectivity still exists. Therefore, how to construct fuzzy relation matrices more impersonally is a challenging open problem that is planned to be resolved.

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