Multidimensional Dynamic Trust Measurement Model with Incentive Mechanism for Internetware

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Abstract. The present trust measurement models of Internetware lack adaptability and time-sensitive, and cannot effectively deal with malicious behaviors. Therefore, based on characteristics of forgotten curve and information entropy theory, this paper proposes a multidimensional dynamic trust measurement model with incentive mechanism for Internetware. Experimental results show that this model can effectively restrain strategic dynamic changing behaviors of malicious nodes, and has good effectiveness and adaptability for different types of nodes.

Keywords: Internetware, trust measurement, time-sensitive, incentive mechanism.

1 Introduction

Internetware is an abstract of complex software in open networks. Internetware can perceive dynamic changes of external network environment. With the changes, entities adjust statically and evolve dynamically according to the network rules and indexes, so that make system have high trust degree [1]. As a new software type, Internetware and its technical system provide methods and technology foundation for researching trust and service quality of complex software [2].

In evolutionary process of Internetware system, people often expect system to converge to target state through effective methods and the selection of interactive strategies. Trust technology of network is a new security method based on network security technology. It strengthens dynamic process of network state and provides strategies for implementing adaptive network security and controlling service quality [3]. Trust is one of the most complex social relationships. It is an abstract psychological cognitive process. So it is hard to express and predict trust. In addition, because of the lack of corresponding incentive mechanism, 1/4 entities are free-rider, which leads to product free-riding phenomenon [4,5].The present research results about trust mechanism have effectively promoted the development of related work, and greatly enriched the understanding about trust relationship between entities. However, there are still some problems as follows.

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(1) Most of the present models adopt expert or average weights method. Once weights are confirmed, it is hard to adjust them dynamically, so that makes trust measurement model lack adaptability.

(2) Most of the present models fail to consider time-sensitive of history behavior data, i.e., time decay problem about the history behavior data.

(3) Most of the present models cannot effectively deal with strategic dynamic changing behavior of malicious entities.

According to the above problems, based on forgetting curve of psychology and information entropy theory, this paper proposes a multidimensional dynamic trust measurement model with incentive mechanism for Internetware. Considering the time decay of history data, this paper introduces time decay factor to compute direct trust entities based on Ebbinghaus Forgetting Curve. In order to improve the accuracy of the recommendation results, this paper computes indirect trust of Internetware entities based on multi-path. In addition, an incentive mechanism is established to encourage entities to select high trust strategy. And a fluctuation-suppress parameter is introduced in order to overcome strategic dynamic changing behavior of malicious entities. In addition, this paper calculates the effectiveness of measurement results by computing evaluation similarity of entities.

2 Related Work

1994, Thomas Beth proposed trust measurement method under open network environment. He divided trust into direct trust and recommendation trust, and adopted probability method to signify trust. Wang Yuan [6] proposed a trust model based on Bayesian network. This model researches how to describe different aspects of trust, so that obtains various properties of entities according to different scenes. Wang Yao [7] solved the problem of recommendation based on Bayesian method. Lu Wen [8] proposed an evaluation method of software reliability. It is a bottom-up calculation process of trust level that can decompose parallel structure, so that calculate trust value of system accurately. However, it only adopts probability method to establish subjective trust model, so that cannot reflect real situations of trust relationship.

In software service synergic system based Agent, trust means a collaborative Agent that can predict subjective possibility of a collaborative activity. Prediction results are affected by evaluation of important degree [9,10]. Because trust between Agents associate with other entities' subjective understanding and fuzziness, it cannot be described and managed by conventional and accurate logic. Subjective trust as a cognitive phenomenon, its subjectivity and uncertainty present fuzziness, so scholars introduced Fuzzy Set into trust management. It not only reflects fuzziness of Agent trust, but also describes trust mechanism between Agents with intuitive and concise semantics. Tang Wen [11] proposed evaluative mechanism of trust based on fuzzy set theory. He gave formalization of trust, and deducted rule of trust to construct a complete subjective trust management model.

Dynamic trust model, one of the most complex social relationships in large-scale distributed systems, involves many factors. These factors are difficult to accurately express and predict. By combining rough-set theory with information entropy theory, Li Xiaoyong [12] put it in an open environment to dynamically build behavior-based data monitoring and analysis of trust measurement model. This method overcame the inadequate problem that traditional models deal with multi-dimensional data.

In addition, Xianfu Meng [13] proposed @Trust model. Puman Bedi [14] proposed trust based recommender system using ant colony for trust computation. And Zhang Shibin [15] proposed trust evaluation method based on cloud model. Above models has greatly promoted the research of trust measurement.

3 Dynamic Trust Measurement Model

By computing direct trust, indirect trust, incentive function and similarity, this paper measures trust degrees of Internetware entities comprehensively.

3.1 Multidimensional Direct Trust with Time Decay Factor (TDF-Trust)

Assume there are N entities in system: P_1, P_2, , P_N, $D_{i,j}^m$ is direct trust of the mth interaction between entity P_i and entity P_j.

$$D_{i,j}^m = \begin{cases} \frac{1}{m}\sum_{k=1}^{m} S_{i,j}^k & m \neq 0 \\ 0 & m = 0 \end{cases} \tag{1}$$

In Eq. (1), m is time-window. $S_{i,j}^{(k)}$ is satisfaction of interaction that entity P_i evaluates entity P_j in the kth interaction, and $S_{i,j}^{(k)} \in [0, 1]$.

In order to solve the problem of thicker dimension, and overcome the subjective judgment on weights, this paper divides satisfaction of interaction into four attributes: Reliability (Rt), Availability (At), Safety (St), and Maintainability (Mt). Thus, the calculation method of satisfaction of interaction that entity P_i evaluates entity P_j in the kth interaction is shown in Eq. (2).

$$S_{i,j}^k = \omega_1 \cdot Rt_{i,j}^{(k)} + \omega_2 \cdot At_{i,j}^{(k)} + \omega_3 \cdot St_{i,j}^{(k)} + \omega_4 \cdot Mt_{i,j}^{(k)} \tag{2}$$

In Eq. (2), ω is the corresponding weight of trust attribute, and $\omega_1+\omega_2+\omega_3+\omega_4$. The corresponding weights represent the importance degrees of satisfaction of interaction. The influences that different trust attributes affect satisfaction of interaction are different. Information entropy theory is uncertainty of an event or measurement of information. It also can be understood as its own information included in the event. Based on information entropy theory, this paper evaluates corresponding weights of different trust attributes. Thus, the calculation method of information entropies for different trust attributes is shown in Eq. (3).

$$H(Xt_{i,j}^{(k)}) = -Xt_{i,j}^{(k)} \cdot log_2 Xt_{i,j}^{(k)} - (1 - Xt_{i,j}^{(k)}) log_2 (1 - Xt_{i,j}^{(k)}) \tag{3}$$

In Eq. (3), $Xt_{i,j}^{(k)}$ is the satisfaction degree of corresponding trust attribute. Let $C(Xt_{i,j}^{(k)})$ be the degree of differentiation that $Xt_{i,j}^{(k)}$ compared with other trust attributes. Its calculation method is shown in Eq. (4). And the calculation method of corresponding weight is shown in Eq. (5).

$$C(Xt_{i,j}^{(k)}) = \begin{cases} 1 - exp(-Sl) \cdot H(Xt_{i,j}^{k}) & Xt_{i,j}^{k} > 0.5 \\ 0 & Xt_{i,j}^{k} \leq 0.5 \end{cases} \tag{4}$$

$$\omega = \frac{C(Xt_{i,j}^{k})}{\sum_{Xt}^{Xt=Rt,At,St,Mt} C(Xt_{i,j}^{k})} \tag{5}$$

In Eq. (4), Sl is the service level that the entity has obtained in last interaction, and $Sl \in 1, 2, 3, 4, 5$. 1 represents the lowest service level, 5 represents the highest service level, and $0 \leq \omega \leq 1$. So we can compute satisfaction of interaction $S_{i,j}^{(k)}$ through Eq. (2) after confirming classified weights.

For improving accuracy and dynamic adaptability of trust measurement, and solving time-sensitive problem of history information, this paper introduces time decay factor $\lambda(k)$. It means the time decay factor in kth interaction, and $\lambda(k) \in (0, 1]$. In the latest interaction, time decay factor is equal to 1; conversely, in the farthest interaction, time decay factor closes to 0. According to characteristics of time decay factor, it can be seen that time decay factor follows the characteristics of Ebbinghaus Forgetting Curve. This curve shows a law of forgotten development. Forgotten process is not balanced. In initial stage, knowledge is soon forgotten, and then slowly. When it achieves some time, knowledge almost is not forgotten.

Internetware is the system with characteristic of ecological population. And memory of entities follows the forgotten development law of Ebbinghaus Forgetting Curve. Based on the forgotten development of Ebbinghaus Forgetting Curve and the law of forgotten development, this paper gives the calculation method of time decay factor, as shown in Eq. (6). The calculation method of direct trust with time decay factor is shown in Eq. (7).

$$\lambda(k) = \begin{cases} 1 & k = m \\ e^{-\frac{1}{k}} & 1 \leq k < m \end{cases} \tag{6}$$

$$D_{i,j} = \begin{cases} \frac{\sum_{k=1}^{m} D_{i,j}^{k} \cdot \lambda(k)}{\sum_{k=1}^{m} \lambda(k)} & m \neq 0 \\ 0 & m = 0 \end{cases} \tag{7}$$

3.2 Multi-Path Indirect Trust (MP-Trust)

In an Internetware system, interaction between entities not only has direct interaction behaviors, but also has indirect interaction behaviors. If there is an interaction path between two entities, there is trust relationship between them. Thus, this paper adopts the method of multi-path to compute indirect trust between entities.

Because the nearer between entities, more reliable the evaluation information, this paper computes indirect trust between entities through multi-path. This method is different from traditional calculation method of simple weighted average. It weights linked degree between entities to compute indirect trust of entities. Fig. 1 shows the multi-path diagram of trust interaction between entities. And $w_{i,j}$ represents trust weight between P_i and P_j.

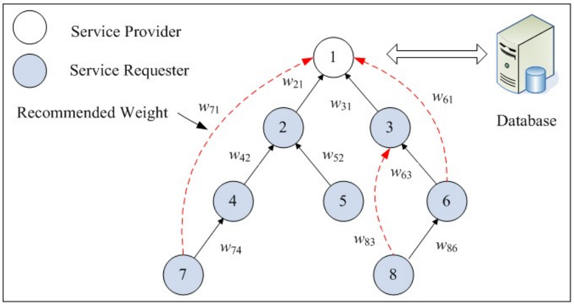

Fig. 1. Multi-path diagram of trust interaction between entities

Assume there is a path between P_i and P_j, $R_{i,j}$ represents indirect trust between P_i and P_j. $IL_{i,j}$ represents interaction path set between P_i and P_j. $IL_{i,j}^x$ represents the xth interaction path between P_i and P_j. $|IL_{i,j}|$ is the number of interaction paths between P_i and P_j. Thus, the calculation method of indirect trust between entities is shown in Eq. (8), and L_x is the nodes set on the xth interaction path between P_i and P_j. k and l are nodes on path L_x. $|L_x|$ is the number of nodes in the xth interaction path between P_i and P_j. Through successful interaction times, this paper confirms trust weight w between two entities. Assume the times of successful interaction between P_k and P_l are $I_{k,l}^{Success}$, and the total times of interaction times are $I_{k,l}^{Sum}$. So the calculation method of trust weight w is shown in Eq. (9).

$$R_{i,j} = \begin{cases} \frac{\sum_{IL_{i,j}^x \in IL_{i,j}}^{|IL_{i,j}|} \sum_{k,l \in L_x}^{|L_x|} w_{k,l}^x D_{k,l}^x}{|IL_{i,j}| \cdot \sum_{k,l \in L_x}^{|L_x|} w_{k,l}^x} & |L_x| \geq 2 \\ 0 & |L_x| = 0, 1 \end{cases} \tag{8}$$

$$w_{k,l} = \frac{I_{k,l}^{Success}}{I_{k,l}^{Sum}} \tag{9}$$

3.3 Global Trust

This paper gives the calculation method of global trust. Assume $M_{i,j}$ is the global trust, so the calculation method is shown in Eq. (10). ϖ_1 and ϖ_2 are respectively direct and indirect weights, and $\varpi_1 + \varpi_2 = 1$. In addition, $\varpi_1 = \frac{Q_{D_{i,j}}}{Q_{i,j}}$, $Q_{D_{i,j}}$

is the times of direct interaction between P_i and P_j, $Q_{i,j}$ is the total times of interaction between P_i and P_j, and $\varpi_2 = 1 - \varpi_1$.

$$M_{i,j} = \varpi_1 D_{i,j} + \varpi_2 R_{i,j} \tag{10}$$

3.4 Incentive Function with Fluctuation-Suppress Mechanism (FIM)

In Internetware system, the inherent ideal of entity is that it maximizes its profit, so as to induce distrust strategy to hold dominant position. Because total profit of distrust is greater than total profit of trust, selfish behavior dominates trust evolution direction of Internetware, which produces free-riding phenomenon. It makes distrust strategy be the first strategy for some entities.

In order to avoid free-riding phenomenon, let $I(j)$ be the incentive function, so the incentive function is shown in Eq. (11). $C(j)$ is the contribution of P_j for system, $E(j)$ is the payoff of P_j, α is the contribution factor, β is the profit factor, and $\alpha + \beta = 1$. $N_{i,j}$ is the fluctuation-suppress parameter. It overcomes strategic dynamic changing behavior of malicious nodes. Thus, the calculation method of fluctuation-suppress parameter is shown in Eq. (12).

$$I(j) = \alpha C(j) + \beta E(j) - N_{i,j} \tag{11}$$

$$N_{i,j} = \left| M_{i,j}^{(n)} - M_{i,j}^{(n-1)} \right| \tag{12}$$

3.5 Similarity

In order to determine effectiveness that P_i measures other entities, this paper depicts effectiveness of trust measurement through similarity. Let $Similar_{i,r}$ be the similarity of trust measurement between P_i and P_r. The bigger similarity between them, the more trust evaluation of P_i. The similarity is calculated by Eq. (13). And $set(i,r)$ is the entity set that have interacted with P_i and P_j. Thus, for computing trust of P_j, it must been determined evaluation effectiveness of P_i. The comprehensive trust of entities is shown in Eq. (14).

In order to normalize the comprehensive trust of Internetware entities, this paper defines a dimensionless $t_{i,j}$, and $t_{i,j} = \frac{T_{i,j}}{T_0}$. T_0 is a system constant, and $0 \le T_{i,j} \le T_0$.

$$Similar_{i,r} = \frac{\sum_{k \in set(i,r))} M_{i,r} M_{r,k}}{\sqrt{\sum_{k \in set(i,r))} M_{i,k}^2} \times \sqrt{\sum_{k \in set(i,r))} M_{r,k}^2}} \tag{13}$$

$$T_{i,j} = \frac{\sum_{q=1}^{n} Similar_{i,q}}{n} \times M_{i,j} + I(j) \tag{14}$$

4 Experiments and Result Analysis

According to the above analysis, this paper gives the experiments and result analysis for this model, and verifies its effectiveness and adaptability.

The hardware experimental environment is Intel Core(TM) Duo 2.66GHz CPU, 2GB memory, Windows XP operating system and Matlab 7.0 experimental platform.

4.1 Effectiveness of Resist Malicious Fluctuation

The ability that system resists malicious fluctuation of entities is verified in this section. This paper respectively simulates dynamic trust changing of malicious entities, which fluctuating periods are 30 and 20 generations, as shown in Fig. 2. Through comparing with PeerTrust model, this paper verifies the effectiveness that model resists malicious fluctuation behavior of entities. In figures, red line shows the fluctuation behavior of malicious entities. TDF is the trust measurement process with time decay factor. FIM is the trust measurement process with incentive function. TDF+FIM is the trust measurement process with time decay factor and incentive function.

From Fig. 2, it can be seen that PeerTrust model and our model both can sense the changes of entities in time. However, PeerTrust cannot reflect time-sensitive of history trust data and resist malicious fluctuation behavior of entities. And the trust model without any trust mechanism cannot resist malicious fluctuation behavior of entities. TDF has certain inhibiting effect. And it reflects time-sensitive of history trust data. FIM reduces trust degree after the malicious fluctuation of entities. But its effect is not obvious, and the fluctuation is big still. TDF+FIM has a good inhibitory effect for malicious fluctuation behavior. It reflects time-sensitive characteristic of history trust data. And trust degree of entity is at a low level after fluctuating, so it verifies effectiveness of this model that resists malicious fluctuation behavior of entities.

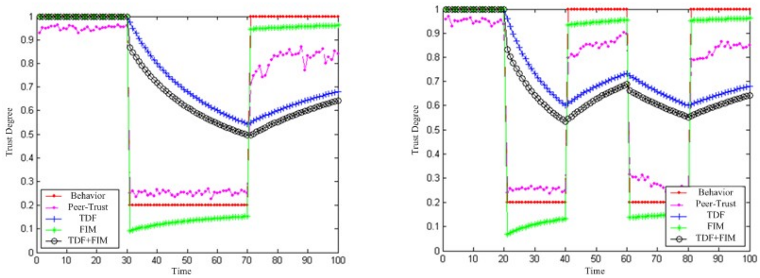

Fig. 2. Dynamic trust changing process of malicious entities

4.2 Effectiveness and Adaptability of Model

For verifying effectiveness and adaptability of this model, this paper simulates trust changing process of normal entities. Fig. 3 shows the experimental result of trust changing process of normal entities. In Fig. 3, the trust changing ranges are respectively 0.6-0.8 and 0.2-1.0. From Fig. 3, it can be seen that when trust fluctuates in certain range, FIM has certain punishment effect for trust fluctuation behavior, but cannot reflect time-sensitive characteristic of history trust information. TDF reflects time-sensitive characteristic of history trust information, and has a good stability. But the punishment force for fluctuation behavior is not very obvious. TDF+FIM not only has better stability, but also has a certain inhibitory effect for fluctuation behavior of malicious entities.

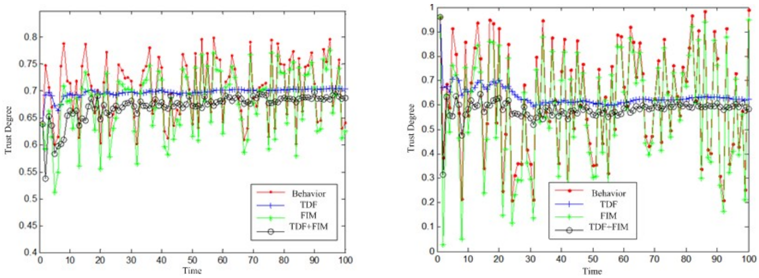

Fig. 3. Dynamic Trust Changing Process of Normal Entities

This paper also measures the trust degree for lazy and learning entities. So-called lazy entities are the nodes with normal learning ability. However, after some interactions, the trust degree of entities always at a low level. And learning entities are the nodes with good learning ability. Learning entities can improve their own trust continually, until reach the stable state. The left figure of Fig. 4 shows the dynamic trust changing process of lazy entities. It can be seen that TDF+FIM has a certain inhibitory effect for fluctuation of entities under situation that initial trust of entities grow fast. And in lazy stage, TDF+FIM does not decrease its trust degree fast. The right figure of Fig. 4 shows the dynamic trust changing process of learning entities. TDF+FIM has a certain inhibitory effect for initial trust fluctuation. But when trust behavior tends to the stable state, TDF+FIM gradually improves the trust degree of entities and tends to the stable state. And compared with TDF, when the trust degree of entities tends to a stable state, trust behaviors of entities have little fluctuation. TDF+FIM can improve the trust degree of entities fast, so it has a good adaptability. Thus, this dynamic trust measurement model has good effectiveness and adaptability for different types of entities.

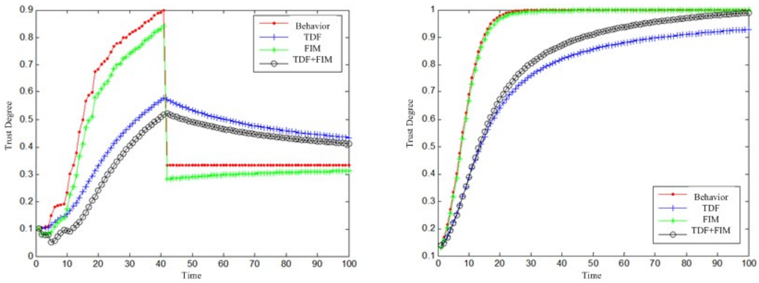

Fig. 4. Dynamic trust changing process

5 Conclusions

According to the shortages of present trust measurement models, most of them are single dimension and fail to consider time-sensitive of history trust data. In addition, they cannot effectively deal with strategic dynamic changing behavior of malicious entities. A multidimensional dynamic trust measurement model with incentive mechanism for Internetware is proposed based on the characteristic of forgetting curve and information entropy theory. This paper proposes multidimensional direct trust with time decay factor, indirect trust based on multi-path indirect trust, incentive function with fluctuation-suppress mechanism and similarity. Through experiments, we can see that this model can effectively inhibit strategic dynamic changing behavior of malicious entities. And this paper verifies that this model has good effectiveness and adaptability for different types of entities.

However, this paper does not consider other trust behaviors and network environment factors. Therefore, the further research on complex trust relationships between Internetware entities is the focus of the future research.

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