Computing Trust Resultant using Intervals

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Abstract— **An important problem in trust management area is to evaluate the trust value among two nodes in a web of trust using intermediate nodes. This is widely used when the source node has no experience of direct interaction with the target. If trust is used to support decision making, it is important to have not only an accurate estimate of trust, but also a measure of confidence in the intermediate nodes and in the final estimated value of trust. In this paper we introduce a novel approach for representation of trust and confidence -both together- using intervals. Based on this representation, we then propose a kind of summation operation that is a method for calculating the resultant of trust opinions. We show that this operator is more accurate for evaluation of trust resultant than the usual method of weighted-averaging. We also report and analyze the results of experiments carried out on a well-known trust dataset which show that our proposed method reduces the average absolute difference and increases the correlation among the inferred and direct values of trust comparing to the weighted-averaging method.**

Keywords- ***trust, confidence, interval, trust interval, trust resultant***

I. Introduction

Recently the concept of trust has obtained an increasingly important role in various fields of computing science including semantic web, computer networks, game theory, multi-agent systems, social networks, e-commerce, etc.

Among different definitions of trust including definitions in [4, 13, 14], the one from Mui et al. [13] is very popular: "[Trust is] a subjective expectation an agent has about another's future behavior based on the history of their encounters."

A trust decision can be a transitive process, where trusting one piece of information or information source requires trusting another associated source. For example, one might trust a book and its author because of the publisher, and the publisher may be trusted only because of the recommendation of a friend. Reputation is considered as a trust measure. Each entity maintains reputation information on other entities, thus creating a "web" that is called the web of trust.

If there is no link between a pair of entities, it means no trust decision has yet been made. This is the case in which trust transitivity can be applied: if A trusts B and B trusts C, then A trusts C. This property is also known as trust propagation or indirect trust estimation. However there is discussion on how much transitivity is valid and which formula or algorithm should be used for calculating the propagated trust value in each field. Multiple researchers are exploring ways to transfer trust within a web of trust. We refer for example to [12, 15, 16].

One important problem in indirect trust estimation is that when an intermediate node reports the value of trust to the target node, how confident this recommendation is and how the level of confidence should be applied in final trust estimation. Another relevant problem is that when two or more intermediate nodes with known confidence levels report the value of trust for a target node independently, how the resultant of these –possibly different- opinions should be computed and what is the confidence in this resultant. As an example, suppose that the source node S receives two values 0.7 and 0.4 on the trustworthiness of the target node D form intermediate nodes A and B respectively. Also suppose that the values of S's confidence in A's and B's reports are 0.3 and 0.8, respectively. What is the resultant of these two different reports and how confident this final S's judgment is?

Many of research works have not taken into account the role of confidence in trust management; and some of them including [8, 9] have used the weighted-averaging method to consider the effect of the confidence in computing trust resultant. In this paper we introduce a novel idea to use the concept of intervals for representation of trust and confidence both together. Based on this representation, we then propose a method for evaluating the resultant of two or more trust opinions. We call this method summation of trust intervals. We also show both intuitively and experimentally that this operator is more accurate for evaluation of trust resultant than the usual method of weighted-averaging.

The rest of this paper is organized as follows: Section 2 describes the related work. In section 3 we introduce our interval notation for representation of trust and confidence. In section 4 we propose the operator of trust interval summation. Our proposed algorithm for inferring trust using interval representation is described in section 5. In section 6 we report and analyze the results of experiments carried out on a trust dataset. Finally we conclude in section 7.

II. Related Work

A variety of research works have been done in the area of trust transition and inferring. In [16, 17] a set of hypotheses and experiments are described for testing how trust is transferred between hyperlinks on the Web. Other more recent works look at how to compute trust transitivity given actual quantities for trust or distrust. A key work in this area is [15] whose goal is to provide a means of merging trust that is robust to noise. Emphasizing personalized trust, as opposed to globally computed values, this approach is described as a generalization of PageRank [1] to the Semantic Web.

Ding et al. in [2] classified trust into two broad categories:

- Referral Trust: Trust to the other's knowledge in a particular domain
- Associative Trust: the value of similarity between two agents' ideas

Then they identified five types of trust, one of which, STT is used in our algorithm. STT stands for Similar Trusting Trust and is an associative trust that evaluates the similarity of two agents' trust knowledge. STT_{ijd} refers to the similarity of agent a_i and agent a_j's referral trust to the other agents within the domain d. Intuitively STT clusters trustors (agents who maintain trust knowledge).

Hasan et al. in [6] used a method for eliminating subjectivity from trust recommendations.

Some works in the area of trust concentrated on trust applications in specific domains. For example, [11] and [19] use the concept of trust in wireless sensor networks and [10] introduces a method for computing global trust in P2P networks.

Among different approaches to trust management, some works paid attention to soft computing techniques. For example [3], [11] and [19] use Ant Colony Optimization algorithm to improve accuracy in trust estimation.

There exist a few works in the area of confidence and its role in trust management in the literature. One of the key works in this area is Josang's one [7] which though does not use the term confidence explicitly, takes into account the concept of uncertainty that has a close relevance to confidence. Josang represents an opinion on trust as a triple {b, d, u} in which b, d and u designate belief, disbelief and uncertainty, respectively.

Josang then introduces a formula for calculating the consensus that is the resultant of two opinions as follows:

"Let $w_p^A = \{ b_p^A, d_p^A, u_p^A \}$ and $w_p^B = \{ b_p^B, d_p^B, u_p^B \}$ be opinions respectively held by agents A and B about the same binary statement p. Then the consensus opinion held by an imaginary agent [A, B] representing both A and B is defined by:

$$w_p^{A,B} = w_p^A \oplus w_p^B = \{b_p^{A,B}, d_p^{A,B}, u_p^{A,B}\}$$

Where

$$b_p^{A,B} = \frac{b_p^A u_p^B + b_p^B u_p^A}{u_p^A + u_p^B - u_p^A u_p^B}$$

$$d_p^{A,B} = \frac{d_p^A u_p^B + d_p^B u_p^A}{u_p^A + u_p^B - u_p^A u_p^B}$$

$$u_p^{A,B} = \frac{u_p^A u_p^B}{u_p^A + u_p^B - u_p^A u_p^B}"$$

In [8] and [9] the value of confidence is estimated using similarity measures. These works use the well-known weighted-averaging method to compute the resultant of trust opinions: when the source entity receives reports from two or more appraisers on the target entity's trustworthiness level, it considers its confidence in each appraiser as that appraiser's weight and calculates the weighted average of all received values.

In [18] a model for the aggregation of trust evidences is proposed that computes confidence scores taking into account the dynamic properties of trust.

III. Representation of Trust and Confidence Using Interval Notation

In trust management area, confidence denotes the capacity in which an entity is assured about its own or another entity's assessment on a target entity's trustworthiness level. For example suppose that entity S asks entity A about D's trustworthiness and A replies as 0.7. However S's (or A's itself) confidence in this opinion may be 0.8.

Since trust and confidence are denoted with two distinct numbers, the calculations dealing with both of them are difficult. We propose integrating these two values in a new representation using intervals. We introduce (1) for this purpose.

$$TI = [C*T, C*T+1-C] \quad (1)$$

Where TI is Trust Interval, and C and T are confidence and trust values respectively.

In other words, to determine the lower bound of the trust interval, we should consider the case when trust is 0 in the uncertainty area. C is the level of confidence and so 1-C is the value of uncertainty. Since trust is reported as T, the minimum of confident trust is C*T. So the lower bound is as (2) shows.

$$L = C*T + (1-C)*0 = C*T \quad (2)$$

To determine the upper bound of the trust interval, on the other hand, we should consider the case when trust has, in the uncertainty area, its maximum value, i.e. 1. So we obtain (3) for the upper bound.

$$U = C*T + (1-C)*1 = C*T+1-C \quad (3)$$

As an example suppose T=0.7. With some different values of C, the trust interval will be as follows:

C = 0 ➔ TI = [0, 1]

C = 0.5 ➔ TI = [0.35, 0.85]

C = 0.8 ➔ TI = [0.56, 0.76]

C = 1 ➔ TI = [0.7, 0.7]

In fact, in the case of C=0, there is no confidence in the opinion of the appraiser at all. This means that no valuable knowledge is obtained about the trustworthiness level of the target. Therefore trust interval is [0, 1]. Note that in the case of C=0, the trust interval is independent of the value of T and is always equal to [0, 1]. As C is increased, the trust interval becomes narrower and the lower and upper bounds approach to T. Finally in the case of C=1, there is absolute confidence in the appraiser's opinion. So the trust estimation is quite accurate and the lower and upper bounds of the trust interval are same and equal to T, that is [0.7, 0.7] in our example.

Although we believe that using an integrated interval for representing both trust and confidence is clearer and more intuitive than using two distinct variables for them, we can again extract the values of trust and confidence from the trust interval anytime needed, especially for evaluation purposes where different methods should be compared. To do that, we may consider (2) and (3) as a system of two equations and solve the system for T and C. Trust and confidence will be obtained as (4) and (5).

$$\mathrm{T} = \frac{\mathrm{L}}{1 + \mathrm{L} - \mathrm{U}} \quad (4)$$

$$C = \frac{L}{T} \quad (5)$$

Our proposed idea of using interval concept for representing trust and confidence is conceptually similar to the notation introduced by Josang in [7]. As we mentioned in section 2, Josnag's model uses a triple to represent belief, disbelief, and uncertainty. We believe that due to using the well-known concept of interval, our notation is more intuitive than Josang's one. However these two notations are convertible to each other. For example we can use (6) and (7) to convert Josang's notation to our one.

$$\mathrm{L} = \mathrm{b} \quad (6)$$

$$\mathrm{U} = 1 - \mathrm{d} \quad (7)$$

Note that in Josang's notation u is not an independent variable and may be obtained having b and d as u = 1-(b+d). The value of u is equivalent to the width of the trust interval in our representation. For example the triple {0.5, 0.3, 0.2} in Josang's model is represented as the interval [0.5, 0.7] in our notation.

IV. TRUST INTERVAL SUMMATION AND ITS PROPERTIES

Suppose that the entity S (source) asks two intermediate entities A and B to report their opinions about the trustworthiness level of the entity D (destination or target). A and B send their replies in the form of trust interval, $[L_A, U_A]$ and $[L_B, U_B]$ respectively (In practice S may first receive from A and B the values of trust and confidence as distinct variables. In such a case it should calculate the trust interval form (1). For example for calculating $[L_A, U_A]$ we should replace C in (1) with S's confidence in A's opinion and T with A's reported trust for D). To determine what is the final assessment of S on D's trustworthiness as the resultant of A's and B's opinions, and in what capacity this estimation is confident, we define a special kind of summation operator for trust intervals. We show this operator in (8) and (9). Note that we do not mean the classic interval summation operator which has a well-known definition in interval algebra, but we mean a novel operator that determines the resultant of two opinions on the trustworthiness of a target entity.

$$L_C = \frac{L_A U_B + L_B U_A - 2 L_A L_B}{W_A + W_B - W_A W_B} \quad (8)$$

$$U_C = \frac{U_A U_B - L_A L_B}{W_A + W_B - W_A W_B} \quad (9)$$

where L_C and U_C denote the lower and upper bounds of the resultant's trust interval, respectively and W is the interval width as defined in (10) and (11).

$$W_A = U_A - L_A \quad (10)$$

$$W_B = U_B - L_B \quad (11)$$

Equations (8) and (9) are obtained from transferring the corresponding equations in [7] into the interval space.

In order to illustrate the concept and applications of interval notation as well as the summation operator defined in (8) and (9), we have computed the sum of some different pairs of intervals and show the results in table 1.

According to (8) and (9) and the results in table 1 we investigate some of the trust interval summation properties in the following:

TABLE I. SUM (RESULTANT) OF SOME TRUST INTERVAL PAIRS

Intervals	[0, 0.25]	[0, 0.5]	[0, 0.75]	[0,1]	[0.25, 0.5]	[0.25, 0.75]	[0.25, 1]	[0.5, 0.75]	[0.5, 1]	[0.75, 1]
[0, 0.25]	[0, 0.14]	[0, 0.2]	[0, 0.23]	[0, 0.25]	[0.14, 0.29]	[0.1, 0.3]	[0.08, 0.31]	[0.29, 0.43]	[0.2, 0.4]	[0.43, 0.57]
[0, 0.5]		[0, 0.33]	[0, 0.43]	[0, 0.5]	[0.2, 0.4]	[0.17, 0.5]	[0.14, 0.57]	[0.4, 0.6]	[0.33, 0.67]	[0.6, 0.8]
[0, 0.75]			[0, 0.6]	[0, 0.75]	[0.23, 0.46]	[0.21, 0.64]	[0.2, 0.8]	[0.46, 0.69]	[0.43, 0.86]	[0.69, 0.92]
[0, 1]				[0,1]	[0.25, 0.0.5]	[0.25, 0.75]	[0.25, 1]	[0.5, 0.75]	[0.5, 1]	[0.75, 1]
[0.25, 0.5]					[0.29, 0.43]	[0.3, 0.5]	[0.31, 0.54]	[0.43, 0.57]	[0.4, 0.6]	[0.57, 0.71]
[0.25, 0.75]						[0.33, 0.67]	[0.36, 0.79]	[0.5, 0.7]	[0.5, 0.83]	[0.7, 0.9]
[0.25, 1]							[0.4, 1]	[0.54, 0.77]	[0.57, 1]	[0.77, 1]
[0.5, 0.75]								[0.57, 0.71]	[0.6, 0.8]	[0.71, 0.86]
[0.5, 1]									[0.67, 1]	[0.8, 1]
[0.75, 1]										[0.86, 1]

1) Sum of two similar or equal trust intervals reflects the confidence increment as the opinions confirm each other. For example sum of two equal trust intervals [0.25, 0.5] and [0.25, 0.5] is [0.29, 0.43]. As mentioned before, reduction of the interval width means increment of confidence. This increment is the result of opinions confirming one another.

2) If we add more than two similar or equal opinions, the width of the result interval becomes even narrower. This means the more opinions add together, the more confidence will be obtained in the resultant. We may consider the sum of multiple equal opinions as a kind of scalar by interval multiplication. Based on this definition, the results of multiplication of numbers 1 through 5 by the interval [0.25, 0.5] are presented in table 2. Note again that we do not mean the classic scalar by interval multiplication, but a novel multiplication operator which describes the resultant of some equal opinions.

3) If we add two or more different (and possibly contradictory) opinions, the sum reflects a reasonable resultant. For example sum of two intervals [0, 0.5] and [0.75, 1] is [0.6, 0.8]. As another example suppose we want to determine sum (resultant) of four people opinions which are given in the form of trust intervals as follows:

P1 = [0.6, 0.8]

P2 = [0.6, 0.8]

P3 = [0.5, 0.75]

P4 = [0.1, 0.3]

The step-by-step calculation shows how the resultant of the first three opinions confirming each other and the fourth opinion contradicting them is obtained:

P1 + P2 = [0.67, 0.78]

(P1 + P2) + P3 = [0.67, 0.75]

((P1 + P2) + P3) + P4 = [0.53, 59]

The resultant obtained in this way is different from the usual weighted average described in the previous section. In fact our approach to calculating the resultant is more accurate and reasonable than the weighted average. We illustrate the reason using an example for now; then in the next section we report the results of experiments confirming this fact. As an example, suppose that the entity S's confidence in A's and B's opinions is 0.9 and 0.45, respectively. In the weighted-averaging approach the weight of A's opinion is considered only twice as the weight of B's opinion, while there is only 0.1 uncertainty in A's opinion but 0.55 uncertainty in B's opinion. In our approach, on the other hand, the effect of each opinion on the resultant depends on its value of uncertainty which is reflected with W_A and W_B in (8) and (9).

4) The proposed operation of trust interval summation is commutative and associative. The commutativity property is obvious from (8) and (9). The proof for associativity, on the other hand, is too long to include here.

5) According to (8)-(11), the proposed summation operation is only defined when $W_A \neq 0$ and $W_B \neq 0$. That is reasonable as if the width of a trust interval is zero it means that there is an absolute belief in this opinion (without any uncertainty). It is meaningless in such a case to try computing the resultant among this opinion and another one.

V. Trust Inference Algorithm Based on the Proposed Approach

A solution to a trust inference problem is a trust value from the interval [0, 1] that describes the amount of trust that the source, say n_0, has for the sink, say n_∞. In this section we first propose our algorithm for calculating the trust resultant. Since the confidence used in this algorithm is estimated based on the similarity measure, we then propose the sub-algorithm which performs this estimation.

A. Trust Resultant Calculation Algorithm

Our algorithm for finding the solution to trust inference problem is shown in Fig. 1. To estimate the value of trust, we should sum all opinions reported on n_∞'s trustworthiness by its neighbors. So the trust interval TI_{sum} considered for denoting sum, is initialized to [0, 1] which is the identity element with respect to trust interval summation. Then all nodes n_k in the trust network from which there is an edge to n_∞ (are neighbors to the sink node), except than n_0 and n_∞, are considered as intermediate nodes. For each node n_k, the source's confidence in n_k and the n_k's trust for n_∞ are considered as C and T respectively and n_k's recommendation about n_∞'s trustworthiness is determined in the form of an interval using (1). We denote this interval by TI_k. Then this interval is summed to TI_{sum} using (8) and (9).

B. Confidence Estimation Subalgorithm

The value of confidence used in the algorithm may be available directly. However in many cases the trust network contains only the values of trust. In such cases the values of confidence should be estimated in some way indirectly. Several works including [7, 8, 19] use similarity measures as an estimation of the confidence the source has in an appraiser (intermediate) node, namely how similar are the opinions of the source and the appraiser in the cases where opinions of both are available, is considered as a measure of the confidence the source node has in the appraiser's recommendations.

The confidence estimation sub-algorithm is shown in Fig. 2. In this sub-algorithm, to estimate the confidence from n_0 to n_k, we calculate MeanDiff that is the mean of absolute differences between n_0's and n_k's opinions on the trustworthiness of all nodes n_i on which both n_0 and n_k have stated their opinions.

TABLE II. Multiplication of Some Equal Opinions (Multiples of [0.25, 0.5])

1*[0.25, 0.5]	2*[0.25, 0.5]	3*[0.25, 0.5]	4*[0.25, 0.5]	5*[0.25, 0.5]
[0.25, 0.5]	[0.29, 0.43]	[0.3, 0.4]	[0.31, 0.38]	[0.31, 0.37]

```
Function InferTrust
Inputs:
    Trust Network (TN),
    source node (n0),
    sink node (n∞)
Output:
    Inferred trust which describes the amount of
    trust that the source has for the sink (TIsum)
Begin
    TIsum = [0, 1]
    For all nodes nk where there is an arc from nk to n∞ do
    Begin
        C = n0's confidence in nk's opinions
        T = nk's Trust for n∞
        TIk = trust interval computed using Equation (1)
        TIsum = TIsum + TIk (Using Equations (8) and (9))
    End
    Return TIsum
End
```

Figure 1. Trust resultant calculation algorithm

```
Function EstimateConfidence
Inputs:
    Trust Network (TN),
    source node (n0),
    appraiser node (nk)
Output:
    The confidence n0 has in nk's opinions
Begin
    sum = 0
    counter = 0
    For all nodes ni in TN
      If T[n0, ni]≠0 and T[nk, ni]≠0
      Begin
          sum = sum + |T[n0, ni] - T[nk, ni]|
          counter = counter + 1
      End
    MeanDiff = sum / counter
    C = 1 – MeanDiff
    Return C
End
```

Figure 2. The confidence estimation subalgotithm

VI. Experiments and Results

To evaluate the accuracy of the resultant calculated using our method and compare that to the weighted-averaging method, we applied both methods to the well-known dataset of Advogato. This dataset contains information of trust among the members of an internet community of programmers and one of its aims is to provide a source for trust experiments. Some other works including [12] used this dataset for evaluating their algorithms, as well.

A. Dataset Characteristics

The dataset of Advogato is a text file including about 71000 lines of data which contains information on trust among about 14000 programmers. Each programmer has stated the value of his/her trust for another programmer in the terms of one of the words Apprentice, Journeyer, or Master. Mapping these words into the numbers in the range [0, 1] is left to the user. We considered the numbers 0.3, 0.6 and 0.9 as the numerical equivalent of the words, respectively. We also considered 0 for the cases where a programmer has not stated any opinion on another programmer.

B. Experiment Results

To evaluate the accuracy of the proposed formula for calculating trust resultant and comparing that to the weighted-averaging method, we used the leave-one-out technique which is a common validation method in trust research works. In this method, for any pairs of nodes, say v_i and v_j, which direct trust of v_i for v_j is available, we also calculate the indirect (estimated) value of trust from v_i to v_j using the proposed algorithm and consider the correlation and mean of absolute error between direct and indirect trust as measures of the algorithm accuracy.

We found all pairs (i,j) in the trust network, which the value of direct trust between them was available. In each case we calculated the estimated value of trust from n_i to n_j in the form of a trust interval using the proposed algorithm. To be possible to compare the results to the weighted-averaging method, we then extracted the explicit value of trust from trust interval using (4). On the other hand, we calculated the estimated trust each node n_i has for node n_j using the weighted-averaging method independently.

To compare the two methods, we compared the results of each method with the direct trust values for all pairs which the direct trust between them was available in the dataset. We computed mean of absolute error and correlation coefficient among each method's results and direct trust values. The results are shown in table 3.

As table 3 shows, mean of absolute error has been decreased in our method to less than half comparing to the weighted-averaging method. On the other hand, correlation among the indirect and direct trust values has been increased as 0.15 comparing to the weighted-averaging method.

VII. Conclusion

In this paper we introduced a novel method for representing trust and confidence concepts, both together, using an interval. Based on this notation we then defined a special kind of summation on the trust intervals which may be used in calculating the resultant of two or more entities' opinions on a target's trustworthiness.

Our proposed notation and summation operation not only represents the trust along with confidence in a more intuitive way, but also provides a good approach to combine opinions confirming or contradicting one another. Furthermore practical experiments on a real trust dataset show that the proposed formula for calculating the trust resultant is more accurate comparing to the weighted-averaging method which is widely used in trust research works.

In future we intend to investigate the effect of measures other than similarity in confidence such as appraiser's distance from the source and time of assessment. We will also study the propagation of interval trust in a trust chain. In addition we are going to study the applications of intervals in analyzing the sources of uncertainty in trust management, eliminating subjectivity from trust assessment and clustering nodes of the web of trust.

TABLE III. COMPARISON OF THE WEIGHTED-AVERAGING METHOD AND OUR PROPOSED METHOD

Method	Mean of Absolute Error	Correlation
Weighted Averaging	0.095	0.76
Our Method	0.043	0.91

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