A Trust-based Pollution Attack Prevention Scheme in Peer-to-Peer Streaming Networks

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Abstract

Nowadays, peer-to-peer (P2P) streaming systems have become a popular way to deliver multimedia content over the internet due to their low bandwidth requirement, high video streaming quality, and flexibility. However, P2P streaming systems are vulnerable to various attacks, especially pollution attacks, due to their distributed and dynamically changing infrastructure. In this paper, by exploring the features of various pollution attacks, we propose a trust management system tailored for P2P streaming systems. Both direct trust and indirect trust are taken into consideration when designing the trust management system. A new direct trust model is proposed. A dynamic confidence factor that can dynamically adjust the weight of direct and indirect trust in computing the trust is also proposed and studied. A novel double-threshold trust utilization scheme is given. It is shown that the proposed trust management system is effective in identifying polluters and preventing them from further sharing of polluted data chunks.

Keywords: Peer-to-Peer Networks, Pollution Attack, Trust Management, Multimedia Streaming.

1. Introduction

1.1. Background and Motivation

The past decade has witnessed the rising of large-scale multimedia social networks, over which millions of users interact with each other and exchange media

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contents in a distributed way. Among all the multimedia social network applications, peer-to-peer (P2P) streaming is popular and successful due to its high scalability, robustness, and satisfactory performance. Currently, there are two categories of P2P streaming systems: tree-based [2, 3] and mesh-based [4, 5]. In tree-based P2P streaming systems, the media content is encoded and divided into small chunks by a root node, and is then distributed to his children nodes. Then, these children nodes forward the received chunks to their children nodes. The data chunks are not forwarded any further at the leaf nodes which reside at the bottom of the tree. In mesh-based P2P streaming systems, the media content is encoded and divided into small chunks by peers. Each peer maintains a buffer map announcing available and desirable chunks. Peers exchange their buffer maps, and then upload or download data chunks according to their interests. Unlike the treebased systems, mesh-based systems do not need to build and maintain a fixed streaming topology, and thus overcomes the bandwidth bottleneck problems existing in tree-based streaming systems. Today's most popular P2P streaming applications, such as PPTV [6], PPStream [7], and SopCast [8], are all mesh-based streaming systems.

In these P2P streaming networks, peers are assumed to be well behaved and non-malicious. To the best of our knowledge, few of them are designed to be resistant to pollution attacks. However, due to their distributed and dynamically changing infrastructure, P2P streaming systems are vulnerable to various attacks, especially pollution attacks. Malicious peers may intentionally forge data chunks or alter received data chunks, and make these polluted data chunks available to other peers. Without the ability to differentiate between malicious peers and good peers, peers are highly likely to request and forward polluted data chunks, consequently degrading the performance of the whole system. Therefore, effective pollution-resistant mechanisms are badly needed for P2P streaming systems.

1.2. Related Work

A number of scholarly work has been published in literature on the design of pollution-resistant mechanisms for P2P streaming systems. In [9], by measuring the PPTV streaming system, the authors showed that without any pollution-resistant mechanisms, the polluted content could spread through much of the P2P network. Then, the authors proposed four possible defenses to pollution attack, namely, blacklisting, traffic encryption, hash verification, and chunk signing. In [10], the authors presented a framework to secure P2P media streaming systems from malicious peers by utilizing a subset of trusted peers to monitor the bandwidth usage of untrusted peers and throttle the malicious peers in the system.In

[11], the authors investigated the scenario that polluters could upload polluted and clean chunks alternatively to avoid being detected, and a trust management system was then proposed to defend this kind of pollution attacks.

On the other hand, trust management mechanisms have been extensively studied in literature for a wide range of applications, such as electronics commerce [12, 13, 14], ad-hoc networks [15, 16, 17], P2P networks [18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29]. However, trust is in nature a complex psychological concept involving a lot of complex properties, such as uncertainty, fuzziness, asymmetry, and time attenuation. The methodology used to model the trust has a significant influence on the performance of the trust management system. Trust models should be tailored to meet the specific requirements of different P2P applications. In this paper, by exploiting the unique features of pollution attacks, we design a trust management system to defend against various types of pollution attacks for P2P multimedia streaming systems. Two closely-related work are [23] and [27]. In [23], the authors developed a fully distributed trust management system named as PeerTrust. PeerTrust adopts the public-key infrastructure for securing trust scores and uses overlay for trust propagation. In [27], the authors proposed PowerTrust, which is a robust and scalable P2P reputation system. They leverage the power-law feedback characteristics to build up a distributed reputation ranking system. PowerTrust can help peers to identify the most reputable peers quickly and accurately. However, both PeerTrust and PowerTrust adopt a fixed weight factor to balance the weight of direct and indirect trust, and use a single-threshold approach to identify dishonest peers. Most importantly, the trust models and the trust updates schemes adopted in PeerTrust and PowerTrust are not tailored to fighting against pollution attacks.

1.3. Main Contributions

The main contributions of this paper are listed as follows.

- A theoretic framework on the modeling of trust management systems to fight against pollution attack in P2P streaming systems is proposed and investigated.
- A dynamic confidence factor is proposed to dynamically adjust the weight
 of direct and indirect trust in computing the trust, which is shown to be
 pretty effective in reducing the negative effects of the bad-mouthing attack
 and the collusion attack. Guidelines on how to deign such a dynamic confidence
 factor are given, and two specific designs of the dynamic confidence
 factor are proposed and investigated.

- A novel approach to model the direct trust is proposed based on the unique features of pollution attacks. It is rigorously proved that the proposed trust model is effective in defending against the on-off pollution attack introduced in Section 4.3.
- A novel double threshold trust utilization scheme is proposed, which is shown to better than the conventional single threshold trust utilization approach.
- The performance of the proposed trust management system is investigated under various types of pollution attacks including bad-mouth attack, persistent attack, on-off attack, and collaborative attack. It is shown that the proposed trust management system is effective in defending against these attacks.

The rest of the paper is organized as follows. Section 2 gives an overview of the design of our trust management mechanism. Section 3 describes the proposed trust management system in detail. In Section 4, the performance of our trust management system under various types of pollution attacks is analyzed. In Section 5, several numerical examples are presented to validate the proposed studies. Finally, Section 7 concludes the paper.

2. System Design Overview

In this paper, we consider a mesh-based P2P streaming network [2]–[5], where all the peers can serve as the uploader and the downloader at the same time. In the proposed system, the media content is encoded and divided into small chunks by peers. Each peer maintains a buffer map announcing available and desirable chunks. Peers exchange their buffer maps, and then upload or download data chunks according to their interests. To defend against various potential attacks that are commonly seen in existing P2P streaming networks, we introduce a trust management system into the P2P streaming network. Under the proposed trust management system, each peer builds up trust records of other peers based on their previous direct transactions or recommendations from other peers. We refer to the trust built on direct interacting experience as direct trust, and refer to the trust built on recommendations from third party as indirect trust. A detail description of direct trust and indirect trust is given in Section 3.

In our trust management system, we assume that there is no central database to store the trust values of peers. Instead, the trust values are computed and stored

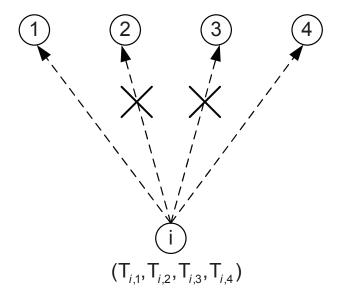


Figure 1: System Model

at each peer itself. We assume there is a trust manager at each peer. One function of the trust manager is to do real-time trust evaluation. To evaluate the trustworthiness of a particular peer, a peer's trust manager sends out the enquiries on the trust values of the target peer to the peers that have direct transactions of both the peer and the target peer. Then, the trust manager computes the trust value of the target peer by doing a weighted sum of the direct trust and indirect trust values. Another important function of the trust manager is to feedback submission. It is responsible for providing recommendations on target peers when it receives trust value enquires on target peers from other peers. The benefit of this assumption is that the proposed trust management mechanism is fully distributed and does not rely on a centralized server. Thus, it can be readily applied to P2P multimedia streaming systems that have distributed structures.

In the proposed trust management system, we use $T_{i,j}(t)$ to denote the trust that user i has on user j at time t. A higher value of $T_{i,j}$ indicates that user i has a stronger belief that user j is trustworthy. The trust values are then used by the peer to decide whether to interact with another peer or not. A peer will only send its data request to the top K peers from all the peers having its desired data chunks based on their trust values. Through this way, peers can reduce the possibility of exposing themselves to malicious peers, and thus can protect themselves from potential pollution attacks. This is illustrated in Fig. 1. Suppose that all the four

peers claim that they have the data chunks that peer i needs, and the trust values of peer 2 and 3 at peer i are low, the trust values of peer 1 and 4 at peer i are high. Then, peer i will only send data request to peer 1 and 4 that are trustworthy.

Detail descriptions of the design of the trust management system is given in the following section.

| Notation | Basic Definition |
|----------------|---|
| $T_{i,j}$ | Trust value of j evaluated by i |
| $D_{i,j}$ | Direct trust value of j evaluated by i |
| $I_{i,j}$ | Indirect trust value of j evaluated by i |
| $\alpha_{i,j}$ | Dynamic confidence factor of i on j |
| $N_{i,j}$ | Number of transactions between i and j |
| $N_{i,j}^c$ | Number of clean chunks that j sent to i |
| $N_{i,j}^p$ | Number of polluted chunks that j sent to i |
| $S_{i,j}$ | Set of peers that have transactions with i, j |
| $C_{i,k}$ | Credibility of k evaluated by i |
| $R_{k,j}$ | k's recommendation value on j |
| λ | Forgetting factor |
| μ | Forgiving factor |
| $	heta_i^P$ | Threshold for detecting malicious peers |
| θ_i^G | Threshold for detecting good peers |

Table 1: Notations and Definitions of Basic Terms

3. Trust Management in P2P Streaming Networks

In our trust management system, we use $T_{i,j}(t)$ to denote the trust that user i has on user j at time t. The value of $T_{i,j}$ is within the range [0,1], with "0" denoting distrust and "1" denoting fully trust. A higher value of $T_{i,j}$ indicates that user i has a stronger belief that user j will upload clean chunks.

Let $D_{i,j}(t)$ and $I_{i,j}(t)$ denote the direct trust and indirect trust that user i has on user j at time t, $T_{i,j}(t)$ can then be computed as follows

$$T_{i,j}(t) = \alpha_{i,j} D_{i,j}(t) + (1 - \alpha_{i,j}) I_{i,j}(t), \tag{1}$$

where $0 \le \alpha_{i,j} \le 1$ is a parameter reflecting user *i*'s confidence of its direct trust over user *j*. A larger value of $\alpha_{i,j}$ indicates that user *i* is more confident of its own

judgement of user j, while a smaller value of $\alpha_{i,j}$ indicates that user i relies more on other peers' recommendation on user j.

In the following subsections, we give an in-depth description of each essential component of the proposed trust management system, which includes the dynamic confidence factor, the direct trust model, the indirect trust model, ways to update the trust values, and how to utilize the trust values. The notations used in this paper are summarized in Table I.

3.1. Dynamic Confidence Factor

Different from the existing literatures (such as [11]) that use a constant to adjust the weight between the direct trust and the indirect trust, in this paper, we define a *dynamic confidence factor* $\alpha_{i,j}$, which is given as

$$\alpha_{i,j} = f\left(N_{i,j}^T\right),\tag{2}$$

where $f(\cdot)$ is a function, and $N_{i,j}^T$ denotes the number of direct transactions that has been made between user i and user j at time T. For notation convenience, we drop t in the discussion.

Basically, $f(\cdot)$ should have the following properties:

- $\forall N_{i,j}^T \in [0, +\infty), f(N_{i,j}^T) \in [0, 1].$
- f(0) = 0, and $\lim_{N_{i,j}^T \to \infty} f(N_{i,j}^T) = 1$.
- $f(N_{i,j}^T)$ is a monotonic increasing function of $N_{i,j}^T$.

Remark: (a). The first property guarantees that the value of the trust defined in Equation (1) falls within the range [0,1]. (b). The second property captures the fact that when there is no direct transaction between user i and user j (i.e., $N_{i,j}^T=0$), user i can only rely on the indirect trust values gathered from other peers to determine its trust of user j (i.e., $\alpha_{i,j}=0$). When the number of direct transactions between user i and user j is sufficiently large, user i can ignore the indirect trust. (c). The third property captures the fact that the confidence of user i on its own judgement of the trustworthy of user j increases when the number of direct transactions between them increases. (d). It is observed that these properties of $f(\cdot)$ are similar to those of cumulative distribution functions (CDF) of random variables [30]. Therefore, the design of $f(\cdot)$ can borrow ideas from the probability theory.

In this paper, we propose two schemes that satisfy all the properties mentioned above to design the confidence factor $\alpha_{i,j}$. The two designs are given as follows.

Confidence Factor Design A (CFDA):

$$\alpha_{i,j} = \frac{N_{i,j}^T}{N_{i,j}^T + c},\tag{3}$$

where c is a positive constant. The value of c has a significant impact on $\alpha_{i,j}$. For the same $N_{i,j}^T$, a larger c will result in a smaller $\alpha_{i,j}$, while a smaller c will lead to a larger $\alpha_{i,j}$. In practice, c can be designed as a tunable parameter that can be tuned by users. This is due to the fact that different peers have different characteristics. Some peers are aggressive, and some peers are conservative. For aggressive peers, they tend to be confidence with their own judgement after a few transactions, and thus they can set a small value for c. For conservative peers, they need more transactions to build up the confidence, and thus they can set a large value for c.

Confidence Factor Design B (CFDB):

$$\alpha_{i,j} = 1 - \beta^{N_{i,j}^T},\tag{4}$$

where $0 < \beta < 1$ is a constant. The value of β significantly affects the increasing rate of $\alpha_{i,j}$. For the same $N_{i,j}^T$, a larger β results in a smaller $\alpha_{i,j}$, while a smaller β leads to a larger $\alpha_{i,j}$. Similar as CFDA, β should be designed as a tunable parameter that can be tuned by users. For aggressive peers, they can set a small value for β ; while for conservative peers, they can set a large value for β .

3.2. Direct Trust

Direct trust is the trust of a peer on another peer based on their direct interacting experience. It is established only based on previous direct transactions between peers. In a P2P streaming system, it is usually determined by two variables: the number of received clean chunks and the number of received polluted chunks. Let $N_{i,j}^c(t)$ and $N_{i,j}^p(t)$ denote the total number of clean chunks and polluted chunks that user i has received from user j at time t, the direct trust $D_{i,j}(t)$ that user i has on user j at time t can be defined as

$$D_{i,j}(t) = g\left(N_{i,j}^{c}(t), N_{i,j}^{p}(t)\right),$$
(5)

where $g(\cdot, \cdot)$ is a two-dimensional function. Basically, $g(\cdot, \cdot)$ should have the following properties:

•
$$\forall N_{i,j}^c, N_{i,j}^p \in [0, +\infty), g(N_{i,j}^c, N_{i,j}^p) \in [0, 1].$$

• $g\left(N_{i,j}^c, N_{i,j}^p\right)$ is an increasing function of $N_{i,j}^c$, and is a decreasing function of $N_{i,j}^p$.

In fact, there are already several direct trust models exiting in the literature. In the following, we list two prevalent direct trust models.

Direct Trust Model A (DTMA):

$$D_{i,j}(t) = \frac{N_{i,j}^c(t)}{N_{i,j}^c(t) + N_{i,j}^p(t)}.$$
(6)

This model has been used in [11] and [26]. It represents the ratio of the number of clean chunks vs the total number of chunks that user i has received from user j. Another model is

Direct Trust Model B (DTMB):

$$D_{i,j}(t) = \frac{N_{i,j}^c(t) + 1}{N_{i,j}^c(t) + N_{i,j}^p(t) + 2}.$$
(7)

This model has been used in [24] and [26]. It is established based on beta-function.

It is observed that if a malicious peer sends clean and polluted chunks alternatively to the peers that request data from it, it can easily keep its trust value above certain threshold if DTMA or DTMB is adopted. For example, if the malicious peer performs the pollution attack by sending one polluted data chunk after sending every two clean data chunks, it can keep its trust value above 0.5. In this way, it can avoid not being detected as a polluter, and keep sending polluted data chunks to the victims. This type of attack is referred to as *on-off attack*. This indicates that DTMA and DTMB are vulnerable to the on-off attack. They cannot be used alone, and must be used together with other techniques to fight against the on-off attack. This inevitably increases the complexity and difficulty of the system design. In this paper, we propose a novel way to model the direct trust, which is resistant to the on-off attack.

Proposed Direct Trust Model (PDTM):

$$D_{i,j}(t) = e^{-\rho N_{i,j}^p(t)} \frac{N_{i,j}^c(t)}{N_{i,j}^c(t) + \eta},$$
(8)

where ρ and η are positive constants, and $e^{(\cdot)}$ is the exponential function. It is easy to verify that the value of $D_{i,j}$ is within the range [0,1], and $D_{i,j}$ is an increasing function with regard to $N_{i,j}^c$ and a decreasing function with regard to $N_{i,j}^p$. The

value of the two parameters ρ and η has a great impact on the value of $D_{i,j}(t)$. Therefore, how to set the value of ρ and η is of great importance to the performance of PDTM. PDTM is rigorously proved to be resistant to the on-off attack when ρ and η satisfy the condition $\rho > \ln(1 + \frac{1}{\eta})$. The details and the proof are given in Section 4.3.

3.3. Indirect Trust

Indirect trust is the trust of a peer on another peer obtained via third-party peers' recommendations. Indirect trust is very important when two peers have little or no direct interactions. Indirect trust is established through trust propagation, i.e., trustworthy peers are more likely to give honest feedbacks than distrusted peers. Usually, indirect trust is determined by two key factors: the credibility of the third-party peer and its recommendation value of the trustee.

Similar to [11], in this paper, we define the indirect trust as

$$I_{i,j}(t) \triangleq \frac{\sum_{k \in S_{i,j}(t)} C_{i,k}(t) R_{k,j}(t)}{\sum_{k \in S_{i,j}(t)} C_{i,k}(t)},$$
(9)

where $S_{i,j}(t)$ denotes the set of peers that have direct transactions with both peer i and peer j. $C_{i,k}(t)$ is the credibility of peer k, and $R_{k,j}(t)$ is user k's recommendation value of user j based on their interaction experience.

In this paper, we design $C_{i,k}(t)$ and $R_{k,j}(t)$ as follows

$$C_{i,k}(t) = D_{i,k}(t), \tag{10}$$

$$R_{k,j}(t) = D_{k,j}(t), \tag{11}$$

where $D_{i,k}(t)$ is the peer i's direct trust on peer k, and $D_{k,j}(t)$ is the peer k's direct trust on peer j. It is observed that k's recommendation on peer j is weighted proportionally by its own credibility. This design has two advantages. First, the value of peer k' recommendation on peer j can not be larger than its credibility. This perfectly emulates human's psychology, i.e., when a person establishes a trust relationship with another person (referee) through a recommender, the trust between the person and the referee is usually not as strong as that between the person and the recommender. Second, peer k' recommendation on peer j must be based on its direct trust value of peer j. In this way, this makes the indirect trust resilient to malicious peers who can manipulate their recommendations to cause maximal damage to the network.

3.4. Trust Updates

Intuitively, the recent interactions should have more weight than old interactions in computing the trust value. In this paper, we assume that the interactions made within the recent Δt time have the same weight, and the weight of the interactions made older than Δt will experience certain attenuation. Mathematically, the update functions can be written as

$$N_{i,j}^{c}(t') = e^{-\lambda \Delta t} N_{i,j}^{c}(t) + \left(N_{i,j}^{c}(t') - N_{i,j}^{c}(t)\right), \tag{12}$$

$$N_{i,j}^{p}(t') = e^{-\mu \Delta t} N_{i,j}^{p}(t) + \left(N_{i,j}^{p}(t') - N_{i,j}^{p}(t) \right), \tag{13}$$

where λ and μ are positive constants, and $t'=t+\Delta t$. In this paper, we refer to λ and μ as forgetting factor and forgiving factor, respectively. We request $\lambda>\mu$, which makes our trust management system remembers the unpleasant interactions longer than the pleasant interactions.

We introduce the trust update functions due to the following three reasons. Firstly, the *forgetting* property provides an incentive for peers to keep uploading clean chunks to maintain or increase their trust values. If the trust computation is only carried out in a cumulative manner without the forgetting property, a peer will have diminishing incentives to behave honestly when it has established a high trust value. This is due to the fact that the negative behaviors will play a little role in changing the peer's trust value at this time. However, if older trust values is discounted with time, a peer's recent behavior always matters and the peer has continuing incentives to behave honestly to maintain or increase its trust values. Secondly, the *forgiving* property allows good peers to wipe off their bad transaction records caused by the bad network conditions. In practice, package loss is inevitable when the network is congested. This will result in incomplete data chunks. If a peer receives such kinds of data chunks, it will treat these data chunks as polluted data chunks and reduce the trust value of the sender though the sender is innocent. With the forgiving property, peers will forget these unpleasant transactions. Finally, the *forgiving* property also gives a chance for the distrusted peers to rejoin the network after a sufficient long waiting time during which they may become good.

3.5. Utilizations of Trust Values

With the trust management system introduced in this section, peers can easily compute the trust values of other peers. The trust values can then be used by peers to identify polluters, and to determine whether to perform a transaction with another peer. A conventional approach is to set up a trust threshold to differentiate

polluters from good peers. For example, peer i can set up a threshold θ_i . If a peer's trust value is below θ_i , peer i identifies it as a polluter and will not perform any further transactions with it. On the other hand, if a peer's trust value is above θ_i , peer i identifies it as a good peer and will perform the next transaction with it. The value of the threshold can be different for different peers. This is due to the fact that different peers may have different perception over the same trust value. This approach is easy to implement. However, it has some deficiencies. For example, if peer i sets a high value for θ_i , it will lose the opportunities to perform transactions with peers whose low trust values are caused by previous bad network conditions. On the other hand, if peer i sets a low value for θ_i , it may make the trust management system vulnerable to potential pollution attacks. Therefore, in this paper, we propose a double threshold approach to utilize the trust values.

Suppose peer i decides to make a transaction with peer j with probability $p_{i,j}(t)$ at time t, then $p_{i,j}(t)$ can be determined by

$$p_{i,j}(t) = \begin{cases} 0, & \text{if } T_{i,j}(t) < \theta_i^P, \\ \chi_{i,j}, & \text{if } \theta_i^P \le T_{i,j}(t) < \theta_i^G, \\ 1, & \text{if } T_{i,j}(t) \ge \theta_i^G, \end{cases}$$
(14)

where θ_i^P and θ_i^G are the thresholds for peer i to identify malicious and good peers, respectively. If the trust value of peer j is below θ_i^P , peer i will identify it as a polluter and will not perform any further transactions with it; if the trust value of peer j is larger than θ_i^G , peer i will identify it as a good peer and will perform the next transaction with it without hesitation. However, if the trust value of peer j is between θ_i^P and θ_i^G , it is hard for peer i to judge whether peer i is a polluter or a good peer experiencing bad network conditions. In this scenario, peer i will perform the next transaction with peer j with probability $\chi_{i,j}$. It is worth pointing out that peer i can set different $\chi_{i,j}$ for different peer j, depending on the content of the potential transaction. For example, peer i is willing to set a high value of $\chi_{i,j}$ for a peer j that has data chunks which are closer to its playback time.

4. System Performance Analysis under Potential Attacks

In this subsection, we give an introduction of the commonly seen attacks in P2P streaming networks, such as *bad-mouthing attack* [31], *persistent attack* [9, 10], *on-off attack* [11, 26], and *collaborative attack* [11, 26]. The performance of the proposed trust management system are then investigated under these attacks.

4.1. Bad-Mouthing Attack

Bad-Mouthing Attack [31] refers to the scenario that a single malicious peer or a group of malicious peers deliberately provides negative recommendations to frame up good peers. If there is only one malicious user, the negative effect of the bad-mouthing attack is quite limited and thus can be ignored. This is due to the fact that the indirect trust is obtained from the recommendations of a group of peers, and a single peer's malicious recommendation is not able to make a big change of the indirect trust value. However, when a group of malicious peers collude and give negative recommendations, the value of indirect trust will be affected.

In our trust management system, the following two ways are adopted to fight against bad-mouthing attacks.

- a). Filtering out potential malicious recommendations. When computing the indirect trust $I_{i,j}(t)$, peer i only select the top K peers based on the value of $D_{i,j}(t)$ from the set $S_{i,j}(t)$. By doing this, a peer can effectively avoid the malicious recommendations from untrustworthy peers. The value of K can be determined by each peer itself based on its own needs.
- b). Reducing the weight of indirect trust. Bad-mouthing attacks are unavoidable as long as recommendations are taken into consideration. Therefore, reducing the weight of indirect trust in the trust computation is a good way to defend against bad-mouthing attacks. The proposed two schemes to dynamically adjust the confidence factor given in equations (3) and (4) can effectively reduce the weight of indirect trust, and thus increase the trust management system's resistant to the bad-mouthing attack.

4.2. Persistent Attack

Persistent attack [9, 10] refers to the scenario that a malicious peer keeps sending polluted chunks to the peers that request data from it. This kind of attacks is very easy to handle when the number of malicious peers are not large. When a malicious peer performs persistent attack, its trust value decreases fast. When its trust value falls below the predetermined threshold, it can be easily detected as a polluter, and will be prevented from further sharing of polluted data. However, if there are a lot of malicious peers existing in the network, the conventional trust management system may be not sufficient. This is because the trust value of a malicious peer is inversely proportional to the polluted data chunks it sends out in conventional trust management systems. Thus, it takes time for the trust value of a malicious peer to drop below certain threshold. If a lot of malicious peers

attack the victim at the same time, the victim may be not able to survive until it can identify malicious peers.

The proposed trust management mechanism is effective in handling with this type of attacks due to the following reasons. First, in our trust management mechanism, a peer will always send data request to those peers that have transactions with it before, and select the top K peers based on the value of $D_{i,j}$ from these peers. In this way, peers can reduce their exposure to malicious peers. Secondly, in our trust management system, the trust value drops exponentially with respect to the number of the polluted data chunks. As a result, the trust value of malicious peers drops below the prescribed threshold within a few data chunks, and thus the victim can identify the these malicious peers quickly.

4.3. On-Off Attack

On-off attack [11, 26] refers to the scenario that a malicious peer sends clean and polluted chunks alternatively to the peers that request data from it. By doing this, the malicious peer can keep its trust value above the predetermined threshold, and thus avoid being identified as a polluter. The on-off attack exploits the fact that most of the trust management mechanisms are designed to tolerate certain levels of unintentionally polluted chunks (such as incomplete data chunks and erroneous data chunks) due to bad network conditions.

To combat the on-off attack, an effective way is to design a trust management system in which the dropping rate of trust value is larger than its increasing rate, i.e., the trust value drops sharply when the peer uploads polluted chunks, and accumulates slowly when the peer uploads the same number of clean chunks. If a trust management mechanism satisfies this condition, we say it is resistant to on-off attack.

<u>Proposition 4.1:</u> The proposed direct trust model given in (8) is resistant to on-off attack when $\rho > \ln(1 + \frac{1}{\eta})$.

Proof: Let the current trust value be $D_{i,j}(t)$. Suppose peer j continuously uploads N polluted chunks to peer i in the following transaction, then the trust value drop denoted by $\Delta D_{i,j}^{de}(t)$ is

$$\Delta D_{i,j}^{de}(t) = D_{i,j}(t) - e^{-\rho \left(N_{i,j}^{p}(t) + N\right)} \frac{N_{i,j}^{c}(t)}{N_{i,j}^{c}(t) + \eta}$$

$$= \left(e^{-\rho N_{i,j}^{p}(t)} - e^{-\rho \left(N_{i,j}^{p}(t) + N\right)}\right) \frac{N_{i,j}^{c}(t)}{N_{i,j}^{c}(t) + \eta}.$$
(15)

On the other hand, if peer j continuously uploads N clean chunks to peer i in the following transaction, then the trust value increase denoted by $\Delta D_{i,j}^{in}(t)$ is

$$\Delta D_{i,j}^{in}(t) = e^{-\rho N_{i,j}^p(t)} \frac{N_{i,j}^c(t) + N}{N_{i,j}^c(t) + N + \eta} - D_{i,j}(t)$$

$$= e^{-\rho N_{i,j}^p(t)} \frac{\eta N}{\left(N_{i,j}^c(t) + \eta\right) \left(N_{i,j}^c(t) + N + \eta\right)}.$$
(16)

The proposed trust management mechanism is resistant to on-off attack when $\Delta D_{i,j}^{de}(t)/\Delta D_{i,j}^{in}(t) > 1$. With equations given in (15) and (16), we have

$$\frac{\Delta D_{i,j}^{de}(t)}{\Delta D_{i,j}^{in}(t)} = \left(1 - e^{-\rho N}\right) \frac{N_{i,j}^{c}(t)}{\eta N} \left(N_{i,j}^{c}(t) + N + \eta\right)
\geq \left(1 - e^{-\rho N}\right) (\eta + N).$$
(17)

It is easy to verify that $h(N) \triangleq (1 - e^{-\rho N}) (\eta + N)$ is an increasing function with regard to N. Therefore, h(N) > 1, $\forall N$, if h(1) > 1, which is equivalent to $\rho > \ln(1 + \frac{1}{\eta})$.

4.4. Collaborative Attack

Collaborative Attack [11, 26] refers to the scenario that a group of malicious peers work together to strategically send polluted data chunks to the target peers. A typical scenario is that one or some malicious peers in the group keep sending polluted data chunks to the target peers, while others send valid data to gain the trust of the target peers and give high recommendation trust values on these malicious peers. The proposed trust management mechanism is quite effective in defending against this kind of attacks due to the adoption of dynamic confidence factor. This is due to the fact that the dynamic confidence factor can effectively increase the weight of direct trust and reduce the weight of indirect trust with the increasing of the number of transactions. When the number of transactions exceeds certain level, the trust value is dominated by direct trust, and the indirect trust can be ignored.

A more advanced type of collaborative attacks is the scenario that a group of malicious peers take turns to send polluted data chunks to the target peers, and at the same time, they give high recommendations on each other. This type of attack is a little complicated and is in general not easy to handle under the conventional trust management mechanisms. However, due to the adoption of the dynamic confidence factor and the proposed direct trust model, the proposed trust

management mechanism is effective in fighting against this type of attack. The individual behavior of each malicious peer in the group is actually same as that of the on-off attack. The difference part is that these malicious peers give high recommendation on each other. Through this way, they can increase the indirect trust values of the attackers, consequently misleading the victims judgement on the attackers. However, as mentioned before, the proposed dynamic confidence factor can effectively reduce the weight of the indirect trust with increasing of the number of transactions. When the number of transactions exceeds certain level, the trust value will be dominated by the direct trust, and the indirect trust can be ignored. On the other hand, as shown in Section 4.3, the proposed direct trust model can effectively prevent the on-off attack. Therefore, with the combination of these two components, the proposed trust management mechanism can easily handle this type of collaborative attacks.

5. Simulation Results

In this section, several examples are provided to evaluate the performance of the proposed studies. It is shown that the proposed trust management is quite effective in fighting against various types of pollution attacks. In the simulations, we consider a network with 10000 nodes. The network topology is generated by BRITE [32], and is then imported to NS-2 [33] to do simulation. Without specific declaration, we assume that CFDA with c=1 is adopted to compute the dynamic confidence factor. We assume $\eta=1$, and $\rho=\ln(1+\frac{1}{\eta})$ for computing the direct trust. The detailed simulation setup for each experiment is clearly described in each individual example studied below.

5.1. Experiment 1: Constant Confidence Factor vs. Dynamic Confidence Factor

In this experiment, we let peer j keep uploading clean chunks to peer i. We assume that peer j is under bad-mouthing attack, and some malicious peers give bad recommendations on peer j for 80 percent of total transactions. Peer i computes the trust values of peer j for 50 interactions based on the constant confidence factor scheme (CCFS) and our dynamic confidence factor scheme (DCFS), respectively. For the CCFS, we assume that the confidence factor is 0.5. For the DCFS, we adopt the CFDA proposed in Section 3. For fair comparison, we assume the direct trust is computed by (6). It is seen from Fig. 2, the values of direct trust is always equal to 1 since peer j keeps uploading clean chunks to peer i. While the values of indirect trust is very low since j is suffering from bad-mouthing attack. It is observed from Fig. 2 that the trust values of peer j obtained based on CCFS

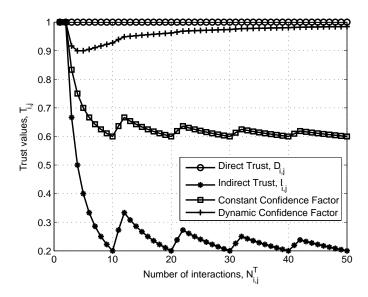


Figure 2: Constant confidence factor vs. dynamic confidence factor

deviate far from the true trust values, while the values obtained based on DCFS are quite close to the true trust values. Besides, the difference between the trust values computed based on DCFS and the true trust values diminishes with the increasing of the number of interactions. This example demonstrates the fact that the proposed DCFS is quite effective in fighting against bad-mouthing attacks.

5.2. Experiment 2: Existing Direct Trust Models vs. Proposed Direct Trust Model

In this experiment, we let peer j perform on-off attacks on peer i. Three different on-off ratios (50%, 20%, and 10%) are considered. When the attacker is in "on" mode, it sends polluted data chunks to the target peer. When the attacker is in "off" mode, it pretends to be a good peer, and sends clean data chunks to the target peer. The on-off ratio denotes the ratio of the duration of the "on" mode to the duration of the entire cycle. As explained before, DTMA and DTMB have similar performance. Thus, in this part, we only compare the performance of the proposed direct trust model with that of DTMA. The trust values of peer j are computed for 50 interactions based on DTMA and PDTM, respectively. It is observed from Fig. 3(a) that the dropping rates are much larger than the increasing rate under PDTM. Therefore, the trust values obtained under PDTM are gradually decreasing in the long run. It is observed that under the 50% on-off attack, the trust value drops below 0.1 within 10 interactions. On the other hand, it is observed

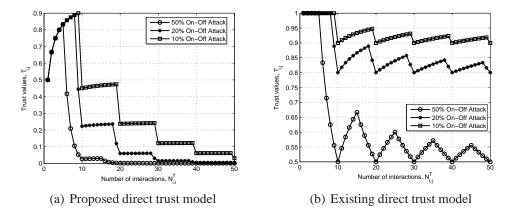


Figure 3: Existing direct trust models vs. proposed direct trust model

from Fig. 3(b) that the trust values computed under DTMA are maintained above certain thresholds. For example, under the 20% on-off attack, the trust values of the attacker are maintained above 0.8. Even under the 50% on-off attack, the trust values of the attacker are maintained above 0.5, which indicates that DTMA is not resistant to the on-off attack.

5.3. Experiment 3: Single Trust Threshold Scheme vs. Proposed Double Trust Thresholds Scheme

In this experiment, we let 20% of the peers to be malicious. 10% of them perform persistent attack, and the other 10% of them perform on-off attack with a 20% on-off ratio. Then, we observe the performance of peer i under different network conditions using the two schemes, respectively. For the single trust threshold scheme, we set the trust threshold of peer i as 0.8. For the proposed double trust thresholds scheme, we adopt the following parameters: $\theta_i^P = 0.5$, $\theta_i^G = 0.9$, and $\chi_{i,j} = 0.5, \forall j$. It is observed from Fig. 4 that peers under the proposed scheme can always achieve higher data rate as compared to the existing single trust threshold scheme. This is due to the fact that the proposed scheme reduces the probability of mistaking a good peer experiencing bad network conditions as a polluter. It is also observed that the gap between the proposed scheme and the single threshold scheme increases when the network conditions become worse. This is because when the network conditions become worse, the trust value of more peers are affected, and thus these peers are regarded as malicious peers by the conventional single trust threshold scheme. On the other side, the proposed scheme allows peer

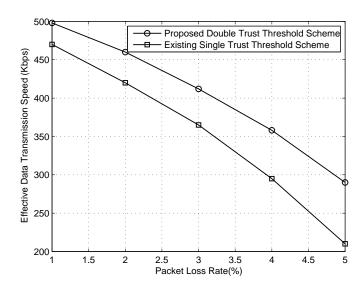


Figure 4: Single Trust Threshold vs. Proposed Double Trust Thresholds

i to perform transactions with these peers with certain probability, and thus results in a higher data rate.

5.4. Experiment 4: Performance under collaborative attack

In this experiment, we assume there are 10 malicious peers carrying out collaborative attack. One of them is chosen to keep sending polluted data chunks to the target peer, while the remaining peers send clean data chunks and give high recommendation to the malicious peer that is chosen to send polluted data chunks. The trust values of the malicious peer sending polluted data chunks and a malicious peers sending clean data chunks are plotted in Fig. 5. It is observed that the trust values of the malicious peer sending polluted data drops quickly with the increasing of the number of the interactions. This is as expected since that the dynamic confidence factor can effectively reduce the weight of indirect trust with the increasing of the number of transactions. When the number of transactions exceeds certain level, the trust value is dominated by direct trust. The trust value of the malicious peer that sends clean data chunks is increasing, since there is no punishment mechanism to prevent peers from giving misleading recommendations in our system. Actually, it is not necessary since the target peer can identify the malicious peer that is sending polluted data chunks, and reject receiving data from it. At the same time, it can also benefit from receiving clean data chunks

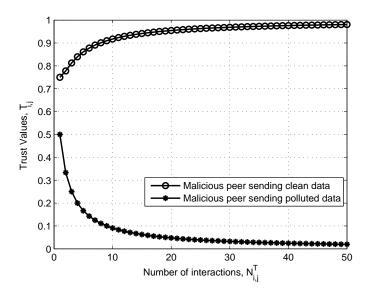


Figure 5: Performance under collaborative attack

from those malicious peers that pretend to be good peers.

In Fig. 6, we investigate the performance of the proposed trust management mechanism under the advanced collaborative attack where malicious peers take turns to attack a target peer. Two scenarios are considered here. Scenario A considerers that 10 peers collude and take turns to attack a target peer. While scenario B considers a group size of 5. It is observed from the figure that the trust values of the malicious peer in scenario A drop slowly than those of the malicious peer in scenario B. This is due to the fact that malicious peers in scenario B attacks the target peer more frequently. In scenario B, each malicious peer sends a polluted data chunk to the target peer after sending four clean data chunks, which is similar as the on-off attack with a on-off ratio of 20%. While in scenario A, each malicious peer sends one polluted data chunk to the target peer after sending nine clean data chunks, which is similar as the on-off attack with a on-off ratio of 10%. This indicates that the group size of the collaborative attack matters. Collaborative attacks with a larger group size are more harmful than those with a smaller group size.

Besides, comparing scenario A with the 10% on-off attack scenario given in Fig. 3(a), it is observed that the trust values of the malicious peer in scenario A drop slowly than those of the malicious carrying out 10% on-off attack, especially during the first 30 interactions. This is due to the fact that in scenario A, the indi-

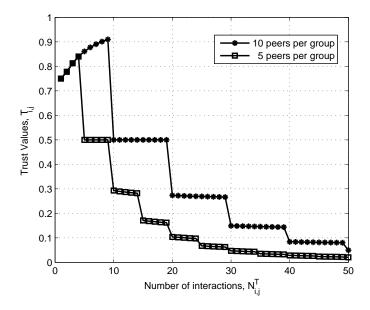


Figure 6: Performance under advanced collaborative attack where malicious peers in the group take turns to attack a target peer

rect trust value of the attacker is high since other malicious peers in the group keep giving high recommendations on the attacker. Thus, the trust value of the attacker drops slow than that of the 10% on-off attack. However, with the increasing of the number of interactions, the effect of the indirect trust on the trust computation decreases due to the role of the dynamic confidence factor. Thus, the gap between the two cases gradually diminishes.

5.5. Experiment 5: The effect of trust values on the number of data requests

In this experiment, we run our algorithm by implementing an event-driven script on the real-world testbed PlanetLab [34]. We observe the number of data requests at 100 peers with different trust values. The trust values of these peers is computed by a new peer that just joins the network and does not have any interactions with others. It is observed from Fig. 7 that the peers with large trust values in general receive more data requests than peers with low trust values. The peers with trust values lower than 0.5 receive much less data requests. This indicates that the proposed trust management mechanism is quite effective in reducing the peers exposure to potential malicious peers. On the other hand, it is observed that the peers with low trust values can still attract some data requests. These data

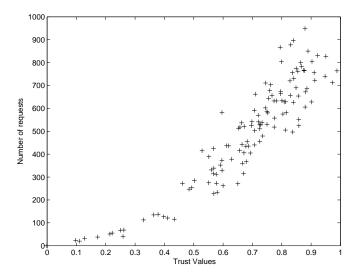


Figure 7: The effect of trust values on the number of data request

requests come from the new peers that just join the network. This is due to the fact that when these peers join the network, they do not have any interactions with other peers. The indirect trust plays a dominate role in computing the trust of other peers. Thus, these new peers are more vulnerable to malicious attacks. They may send data requests to those peers with low trust values if they receive misleading recommendations.

5.6. Experiment 6: Performance comparison between the proposed trust management system and PeerTrust

In this experiment, we compare the performance of the proposed trust management system with that of the existing PeerTrust given in [22]. For our scheme, we use the same simulation parameters as in example 3. For each scenario, we let half of the malicious peers perform persistent attack, and half of the malicious peers perform on-off attack with a 20% on-off ratio. The network condition is emulated by randomly adding a packet loss rate between 0% and 2% at each peer. It is observed from Fig. 8 that when there is no malicious peers in the network, the proposed trust management system performs the same as PeerTrust. However, with the increasing of percentage of malicious nodes, the advantages of the proposed trust management system become evident. This is as expected since the proposed trust management system takes the features of pollution attack and the

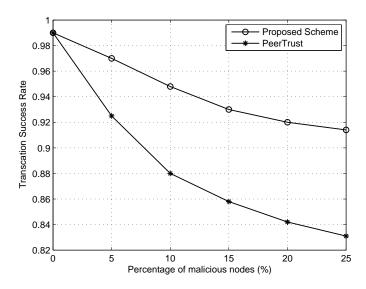


Figure 8: Proposed trust management system vs. PeerTrust

network conditions into consideration when it is designed, while PeerTrust does not.

6. Discussion and Future Work

6.1. Secure Transmission of Indirect Trust Values

Due to the distributed nature of P2P multimedia streaming networks, the unauthorized manipulation of indirect trust values can happen during the transmission. Thus, it is very important to guarantee secrecy and integrity of the trust data. This can be achieved by a PKI-based (Public Key Infrastructure) [35] scheme. When a peer i wants to evaluate the trustworthiness of peer j, it initiates an enquiry on the indirect trust value of peer j, and sends its public key together with the enquiry. Then, the peers who have transaction experience with peer j, encrypt their responses with peer i's public key and sign the responses with their own private keys. Then, these peers sends the signed encrypted responses to peer i together with their public keys. Upon receiving these responses, peer i verifies their signatures with the attached public keys and decrypts the responses with its own private key. The fact that the responses are signed with the responding peers' private keys allows the detection of integrity violations of the trust values and the authenticity

of their origins. The fact that the trust values are encrypted with peer *i*'s public key guarantee the confidentiality of the trust data transmission.

6.2. Joint Design of Trust Management and Incentive Mechanisms

Indirect trust plays a significant role in computing the trust value of a target peer when a peer does not have much interactions with the target peer. However, without effective incentive mechanisms, peers have no incentive to cooperate with each other, and thus the trust records based on other peers' recommendations cannot be quickly established. Therefore, effective incentive mechanisms [36, 37] are crucial for the successful implementation of the proposed trust management mechanism. On the other hand, trust management mechanism are very important for P2P streaming systems with incentive mechanisms. Without effective measures to identify malicious peers, the polluted data chunks could be disseminated to the whole network more quickly in a P2P network with incentive mechanisms than that without incentive mechanisms. This is due to the fact that peers are motivated to upload data chunks to each other to earn points or monetary rewards in a P2P system with incentive mechanisms. Without the ability to identify malicious peers, peers are more likely to forward polluted data chunks, consequently degrading the performance of the system. Therefore, trust management and incentive mechanisms should be jointly designed to defend against both malicious attacks and selfish users. We leave this as our future work.

6.3. Tuning of the Parameters

In the proposed trust model presented in this paper, there are a lot of tunable parameters. The value of these parameters plays a significant role in the effectiveness of the proposed trust model. Thus, how to optimally choose the values of these parameters is of great importance. In this paper, we deign these parameters as tunable parameters and let the users decide these parameters based on their own benefits. This is due to the fact that different users have different requirement. It is clear that this design offers great degree of freedom, and benefits each individual peer. From the perspective of the whole P2P community, this may not be optimal. Besides, the value of these parameters may have an impact on the network topology resilience, the streaming quality, and the network awareness [38]. Thus, how to choose these parameters such that the performance of the whole community can be optimized needs to be investigated. We leave this as our future work.

7. Conclusion

In this paper, a trust management system to fight against various kinds of pollution attacks for P2P multimedia streaming systems are proposed by exploring the unique features of pollution attacks. A dynamic confidence factor is proposed to dynamically adjust the weight of direct and indirect trust in computing the trust, which is shown to be pretty effective in fighting against the bad-mouthing attack. Guidelines on how to deign such a dynamic confidence factor are given, and two specific designs of the dynamic confidence factor are proposed. Besides, a new direct trust model that is proved to be resistant to the on-off pollution attack is proposed and investigated. The performance of the proposed trust management mechanism under various types of pollution attacks is then investigated. Finally, several numerical examples are presented, which show the superiority of the proposed trust management system.

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