Reputation-Based Trust Management for P2P Networks

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Abstract

The open and anonymous nature of a P2P network makes it an ideal medium for attackers to spread malicious content. In this paper, we describe a reputation-based trust management protocol for P2P networks where users rate the reliability of parties they deal with, and share this information with their peers. The protocol helps establishing trust among good peers as well as identifying the malicious ones.

Results of various simulation experiments show that the proposed system can be highly effective in preventing the spread of malicious content in P2P networks.

1 Introduction

A peer-to-peer (P2P) network is a computer network that does not have fixed clients and servers but a number of peer nodes that function as both clients and servers to the other nodes in the network. Although in general any networking technology that uses this model can be considered as P2P, such as the NNTP protocol used for transferring Usenet news or a wireless ad hoc network, the term is most frequently used to refer to file sharing networks over the Internet, such as Gnutella, FastTrack, and Napster. In this paper, we also focus on P2P file sharing systems and use the term "P2P" mostly to refer to this particular application of the more general concept.

By the nature of its architecture, a P2P file sharing system provides an open, unrestricted environment for content sharing. However, this openness also makes it an ideal environment for attackers to spread malicious content such as the VBS.Gnutella worm [11].

Reputation-based systems are used to establish trust among members of on-line communities where parties with no prior knowledge of each other use the feedback from their peers to assess the trustworthiness of the peers in the community [10]. One well-known such system is the rating scheme used by the eBay on-line auction site [6].

In this paper, we propose a reputation-based, distributed trust architecture for P2P networks to identify malicious peers and to prevent the spreading of malicious content. The protocol is based on the query-response architecture of the first generation P2P networks and is suitable for operation in a Gnutella- or Kazaa-like system.

The protocol we propose is described in Section 2. The rationale for its design is discussed in Section 3. Security extensions on the basic protocol are discussed in Section 4. Results of the simulation experiments testing the protocol's effectiveness are presented in Section 5. Earlier protocols with a similar scope and their differences from our proposal are discussed in Section 6. Section 7 concludes the paper with a discussion of the future work necessary for a practical deployment.

2 The Basic Protocol

A query in a P2P file sharing system typically returns many different versions of the queried resource, among which some may be malicious. The aim of our protocol is to distinguish the malicious responses from benign ones, using the reputation of the peers providing each version. Since in P2P networks a central server is typically not available, our protocol relies on the P2P infrastructure to obtain the necessary reputation information when it is not locally available at the querying peer.

In this section, we give a high-level description of the basic protocol. The rationale for the design choices are explained in the next section and certain extensions on the basic protocol are discussed in Section 4.

2.1 Resource Query

A query message is sent out by a peer to search for a resource with the specified properties. The query message includes, among other fields, the *query ID number*, denoted by qID, which is a counter value maintained by each peer to identify the queries it issues.

The response messages sent by the peers with the requested resource includes, among other fields,

- ID of the querying peer (QID),
- ID of the responding peer (RID),
- query ID number (qID),
- a one-way hash of the file being offered.

The whole response message is hashed and signed by the responder. Here, the hash of the message signed by the responder serves the function of a challenge in a challenge-response authentication protocol. Inclusion of the (QID, RID, qID) triple in the challenge guarantees its freshness against replay attacks.[1] Inclusion of the rest of the message in the signature is for integrity protection. The one-way hash of the file being offered is included in the response to enable the querier to identify different versions of the file and to group the identical ones together, which will be used to assess the trust level of each version.

2.2 Trust Assessment

Upon receiving the responses to its query, the querier groups them according to the file hash values contained in the messages, and a *trust score* is calculated for each group according to the reputation of the peers who provided that response. If the querier has previous information on a sufficient number of the peers who provide a file version, the trust score for that version is calculated from the local *trust ratings*. Otherwise, a group of peers who provide the file but were not known previously are selected and a *trust query* for them is issued. The responses to the trust query are weighed according to the *credibility ratings* of the respondents and a trust score for that file version is calculated. At the end, the trust scores of the different versions are compared and the one with the highest trust score is selected for download.

The trust evaluation function used for the calculation of the trust scores is described in detail in Section 2.4.

2.3 Trust Records and Ratings

In our system, the outcomes of past transactions are stored in *trust vectors*, maintained by the peers that make the download. Every peer maintains a trust vector for every other peer it has dealt with in the past.

Trust vectors are constant-length, binary vectors of ℓ bits, where ℓ is typically 8, 16, or 32. A 1 bit represents an honest transaction, a 0 represents a dishonest one. An integer variable accompanies each vector, specifying the number of significant bits in it. The result of a new transaction is written at the most significant bit, shifting the present bits to the right. The process is illustrated in Figure 1.

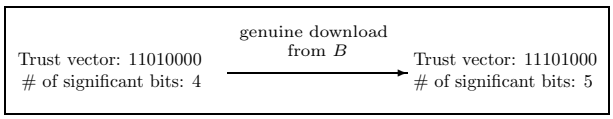


Figure 1: Peer A's update of its trust vector on B after an honest transaction. In this example $\ell = 8$.

A trust vector with m significant bits is read as an m-bit integer and divided by 2^m for conversion into a scalar *trust rating* in the $[0, 1)$ interval.[2] A separate *distrust rating* is also computed from the complement of the trust vector, for reasons explained in Section 3. An example computation of the trust and distrust ratings is shown in Figure 2.

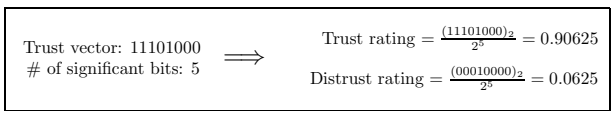


Figure 2: Computation of the trust and distrust ratings from the trust vector.

Throughout the trust evaluation process, the criterion of *minimum distrust* is given priority in trust comparisons over *maximum trust*. The most trustworthy peer in a group is taken to be the one with the highest trust rating among those who have the lowest rating of distrust.

2.4 The Trust Evaluation Function

When responses in regard to a resource query arrives, the querying peer organizes them into groups according to the file hash value they offer, each group corresponding to a different version of the resource queried. A trust score for each version is then calculated from the trust rating of the peers offering it as follows:

The threshold θ_T specifies the number of peers to be considered for a version's trust calculation. For a group of peers G, we use the notation $known(G)$ for denoting the set of peers in G about whom a trust record is available locally, and $unknown(G)$ for $G - known(G)$. We denote the cardinalities of these sets by $n_k(G) = |known(G)|$ and $n_u(G) = |unknown(G)|$.

[1] If the wrapping of the qID counter is a concern here, the hash of the whole query message can be included in the response as well.

[2] Here, the use of 2^m as the divisor instead of $2^m - 1$ enables distinguishing among the straight-1 trust vectors according to the length m, favoring longer all-honest histories over shorter ones.

The trust score for a group G is calculated locally if there is sufficient local information; that is, if $n_k(G) \geq \theta_T$. First, the peers in $known(G)$ are sorted by their trust rating, according to the min-distrust-max-trust criterion. The highest ranking θ_T peers are selected and the signatures on their responses are verified. Provided that all signatures are verified correctly,[3] the trust and distrust score of the file version offered by G is determined as the average of the trust and distrust ratings of the selected peers.

If there is not sufficient information on G (i.e., $n_k(G) < \theta_T$), then a set of $\theta_T - n_k(G)$ random peers in $unknown(G)$, denoted by $queried(G)$, are selected to be queried about.[4] The signatures on these peers' messages are verified and a *trust query* bearing their IDs is issued. Upon the arrival of the responses to this query, a *queried trust rating* is calculated for each peer in $queried(G)$. The trust and distrust score of the file version offered by G is determined as the average of the trust and distrust ratings of the peers in $known(G)$ and $queried(G)$.

At the end of the evaluation, the file versions are sorted by their trust scores, according to the min-distrust-max-trust criterion, and the highest ranking one is selected for download.

At this point, it would be wise to have another safety check on the trust score of the file to be downloaded since a file offered only by malicious peers may be the highest ranking one, probably due to the lack of any alternative versions. A possible threshold here can be to allow the download of only those files with a higher trust score than distrust. Or, as a safer alternative, only the download of those files with a zero distrust score may be allowed, which would not be too restrictive given that the neighborhoods are sufficiently large.

2.5 The Trust Query Process

As mentioned above, a trust query is issued when there is not enough local information about the peers who offer a file. The contents of a trust query message is similar to that of an ordinary resource query message, and the responses are authenticated in the same fashion.

The credibility of the responses is evaluated according to the past records of the respondents. The results of the past references of a peer are recorded in binary *credibility vectors*. These vectors are managed very similarly to the trust vectors: A 1 represents a good reference in the past, a 0 represents a bad one. The vectors are maintained as ℓ-bit variables and are converted into scalar *credibility ratings* in $[0, 1)$ by division by 2^m , where m is the number of significant bits. A *discredibility rating* is computed accordingly from the complement of the credibility vector.

The threshold θ_C specifies the number of responses to be considered in a queried trust calculation. When the responses to a trust query arrives, the querying peer sorts the responses by the credibility rating of their senders. Among them, the highest ranking θ_C responses are selected.[5] The signatures on the selected responses are verified.

The main piece of information contained in a trust query response is the respondent's trust and distrust ratings for the queried peer. Once the responses for the calculation are selected and authenticated, the *queried trust rating* is calculated as the average of the trust ratings in these messages, weighted by the net credibility ratings of their senders, where the responses with a higher discredibility than credibility are left our of the calculation. That is, if peer A issued a trust query on peer B, and the responses of peers $R_1, R_2, \ldots, R_k$, $k \leq \theta_C$, qualify for consideration, where R_i's trust rating for B is t_i and A's credibility and discredibility ratings for R_i are c_i and d_i respectively, then A's queried trust score on B is

$$\frac{\sum_{i=1}^{k}(c_i - d_i)t_i}{k}. \tag{1}$$

The queried distrust rating is calculated in the same fashion, using the respondents' distrust ratings of B.

The operation of the trust query and evaluation protocol is illustrated in Figure 3.

2.6 File Download

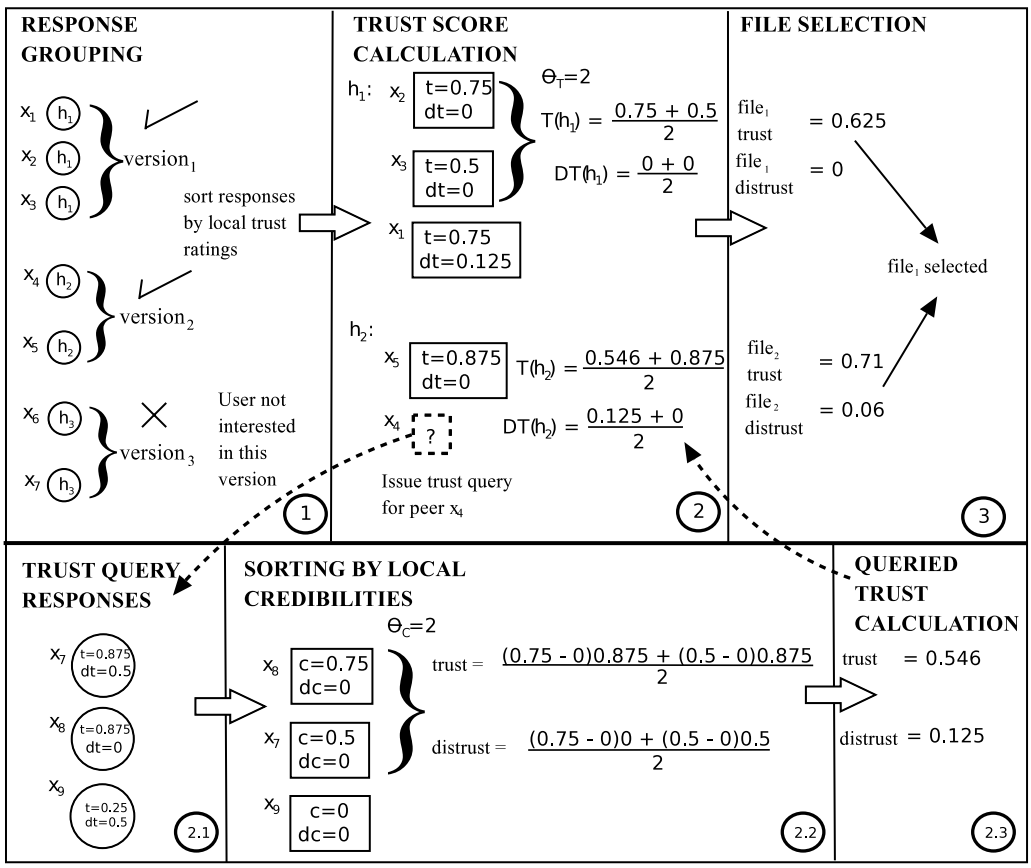
Once the file version to be downloaded is decided, one or more peers who provided that response are selected according to QoS or some other criteria—but not according to the peer's trust ratings which would result in the overloading of the trusted peers—and the file is downloaded from the selected peers.

It is possible that a peer who provided the right hash in a file query was in fact malicious and that it will send the malicious file if selected for download. The correctness of the hash can be checked once the file is downloaded completely, but then the attacker will have succeeded at least in wasting the bandwidth of the querier. Moreover, if multiple sources are used for the download, which is a common way of downloading large files, a hash mismatch detected after the file

[3] If a selected peer's signature fails the verification, it is replaced by the next highest ranking peer in $known(G)$ and the average is calculated accordingly.

[4] If $n_u(G) < \theta_T - n_k(G)$, then all peers in $unknown(G)$ are selected.

[5] If there are fewer than θ_C responses in total, all responses are selected.



THE LOCAL DATABASE

TRUST RECORDS

Peer	*Vector*	*# of bits significant*
x_1	11000000	3
x_2	11000000	2
x_3	10000000	1
x_5	11100000	3

CREDIBILITY RECORDS

Peer	*Vector*	*# of bits significant*
x_7	10000000	1
x_8	11000000	2

Figure 3: An illustration of the trust evaluation protocol. In response to a file query, three different replies are received among which the querier is interested in the first two. A trust comparison among these two versions follows. In this process, sufficient information is not available locally on the providers of the second version. Hence, a trust query is issued for peer x_4. At the end of the calculations, the first version turns out to be the one with a better trust score and will be downloaded from some subset of the peers $\{x_1, x_2, x_3\}$.

download will not identify the malicious source, possibly ruining the reputation of the honest peers along with that of the malicious ones. To prevent this potential threat, we describe a two-level hash scheme in Section 4.3 which detects falsely reported hashes early in the download.

2.7 Update of Trust and Credibility Ratings

After the file download is complete, a user is asked to judge the file as benign or malicious. If it is rated benign, the trust rating of the peer(s) from whom the file is downloaded is upgraded. Otherwise, the rating of the peer who sent the malicious content and the rating of those who contributed to its selection are downgraded. The difference between the two cases is

due to the following fact: A malicious peer may well offer a right hash during a query in the hope of being selected and, if selected, sends the malicious content. Therefore, merely a reference for a good file is not sufficient for upgrade of the trust rating. On the other hand, if a downloaded file turns out to be malicious, all peers who offered that file can be assumed to be malicious.

The update of the credibility ratings is slightly more complex: A peer's credibility rating is updated at the end of a file download if that peer has given an authenticated opinion on a peer whose trust rating ended up being updated as the result of that download.

A credit rating update's direction (i.e., its being negative or positive) is determined according to the opinion given and the direction of the trust rating that is updated: If a peer's trust rating is upgraded and some peer gave a positive opinion on that peer, or if both the trust rating update and the opinion were negative, then the credibility of the referring peer is upgraded. Otherwise, it is downgraded.

Another important point here is how an opinion is classified as "positive" or "negative". Since the distrust rating has priority in evaluation over the trust rating, an opinion with a non-zero distrust rating is considered a negative one. An opinion with a positive trust rating with zero distrust on the other hand, which implies a trust rating of 0.5 or higher, is considered a positive opinion.

3 Design Rationale

3.1 Basic Trust Evaluation Process

The idea of using the feedback from other peers to assess the trustworthiness of a resource/peer is a fundamental characteristic of reputation systems [10]. In our protocol, this process is carried out in a distributed fashion due to the lack of a centralized server in P2P systems in general.

In our trust rating calculations, opinions of peers are weighted by their trustworthiness. Moreover, the evaluation is restricted to a few (θ_T or θ_C) most trusted responses. This has the purpose of preventing some low-trust responses discrediting a reliable resource/peer supported by sufficiently many trusted peers, as well as limiting the number of responses to be authenticated, which, unless restricted in number, can be a performance bottleneck.

A special feature of our trust evaluation function is the separate treatment of the distrust ratings. Although both the trust and distrust ratings are derived from the same trust vectors, handling the distrust ratings separately has the additional feature of not letting a dishonest dealing be erased easily by a few honest transactions, which closely models real-life trust relations where a single dishonest transaction in someone's history is a more significant indicator than several honest transactions.

An important factor to be considered in reputation-based systems is temporal adaptivity; that is the ability to respond rapidly to changing behavioral patterns. Our trust rating design with binary vectors makes an efficient exponential aging scheme with an aging factor of 0.5. Besides, implementing the aging scheme by fixed-length registers rather than floating point arithmetic has the desirable feature of enabling peers to cleanse their history by doing a certain amount of honest community service after a bad deed. Note that this service must be done to the same person who was cheated, and hence a bad transaction on record will take some time to be erased completely. The number of faithful transactions required to cleanse a bad record is determined by the length of the trust vector, ℓ. If it takes a considerable amount of time to have two transactions happen between the same pair of users, $\ell = 8$ could be a reasonable choice. Higher values of ℓ could be preferred for highly active systems or in systems where cheating is considered a major offense.

3.2 Queried Trust Evaluation

A fundamental decision in our design was to use a credibility rating system separate from the trust ratings. The main risk of using the trust ratings for credibility evaluation comes from coordinated attacks where some malicious peers do as much faithful public service as they can and build a strong reputation, and then use their credibility for supporting others who spread malicious content. Having separate trust and credibility rating systems precludes such attacks.

One aspect different in the treatment of the credibility and the trust ratings is the way they are used when ranking the file or trust query responses. The trust ratings are ranked by the min-distrust-max-trust criterion whereas the credibility ratings are ranked simply by the rating values. This difference is due to the difference in the significance of a negative entry on the vectors: A negative entry on Alice's trust vector for Bob is due to a problematic file served by Bob in the past. On the other hand, a negative entry on Alice's credibility vector for Bob does not necessarily imply a wrongdoing on Bob's part but may simply be due to Alice and Bob's having different experiences with a third peer Charlie who may be demonstrating inconsistent behavior, possibly with the specific aim of creating discredibility among good peers. It

is due to this difference in reliability[6] that the responses to a trust query are ranked by the credibility ratings alone, instead of using a min-discredibility-max-credibility ranking.[7]

Like the safety check discussed at the end of Section 2.4 against the low-trust responses that may enter into the top θ_T in the local trust evaluation, we decided that the top θ_C responses in a trust query should be evaluated only if they have a credibility rating higher than discredibility. Accordingly, the factor for weighting the trust query responses in Equation (1) is taken as the net credibility ratings, $c_i - d_i$, rather than the credibility ratings alone.

3.3 File Download and Update of the Ratings

Once the file version to be downloaded is decided, the peer to download it from is selected randomly among those who offered that version without regard to the trust ratings. This way of selection has the desirable feature of enabling new peers to build a reputation as well as not overloading the trusted peers.

We have already explained in Section 2 why the update of trust ratings after a download is limited to the peers from whom the file was downloaded and, in case the file was malicious, to those who were authenticated references for the file. The main reason was that we could not decide conclusively about the other peers involved. It is due to the same reason that the credibility ratings are updated only for those peers who are authenticated references for someone whose trust rating is updated as a result of the download.

Note that, in a trust query, the top θ_C responses are authenticated regardless of their net credibility rating's being positive or negative, despite the fact that the responses with a negative rating would not be used in the calculations. This is necessary to give the peers with a zero or negative net credibility rating a chance to upgrade their ratings. Otherwise, if such an opportunity were not present, it would not be possible for the new peers to build a credibility, and the credibility system would be totally useless. Similarly, it would not be possible for the good peers who have somehow got a negative entry on their credibility history to turn their ratings to positive again.

[6]Here, it may be argued that since the credibility ratings are not as reliable as the trust ratings, it would be better to use the trust ratings in their place. Even though the trust ratings may indeed be better against uncoordinated attacks, they would be useless when attackers coordinate as discussed earlier in this section.

[7]Otherwise, established good peers with a high credibility but a tiny discredibility caused by some inconsistent peer would be ranked lower than a newcoming peer with no credibility or discredibility.

4 Security Extensions

In the section, we discuss extensions on the basic protocol to provide secure and reliable trust information in the presence of active attackers.

4.1 Key Management

Our system makes use of digital signatures for authentication of critical messages. The core trust issue in public key systems is to ascertain that a public key received on-line indeed belongs to the claimed party. The classical solution to this problem is by trusted certification authorities, which may not be an option in the P2P systems that are totally decentralized. On the other hand, most P2P systems are pseudonym-based systems, where the question is to bind the public keys to pseudonyms, not to real-life identities. A natural solution here is to make the public key of a peer also its pseuodnym. That is, in an RSA-based system for example, the public exponent-modulus pair (e, n) can be taken as the pseudonym of the entity using it.[8] In such a system, there will be no question of the public key's authenticity when the trust information from a certain pseudonym is to be verified.

4.2 Denial of Service Protection

The requirement of responding to every relevant query with a digital signature is likely to be an excessive burden on the peers. Moreover, it can easily be exploited for denial of service attacks by attackers continually issuing many high-match queries. To protect against this threat, a puzzle scheme is used adding an extra round to the protocol: In the initial response, the file hash is sent without any signature. Instead, the responding peer includes a puzzle to be solved by the querier, such as finding a string whose MD5 output matches a certain value [2], which should be answered correctly before a signature is issued. Then the querying peer decides on which file versions he is genuinely interested in and solves the puzzles of a limited number of the respondents for each version.

4.3 Avoiding Fake File Downloads

Another avenue of attack for sending malicious files is to provide the hash of a benign file during the query-response process but, if selected as the download source, to send the malicious file during the download. Such attacks can be detected if the hash of a downloaded file is checked before opening. However, the time and bandwidth of the downloader would be wasted, which

[8]If the pseudonyms are desired to be of uniform length such as an ID number, a one-way hash of the public key can be used.

is exactly the purpose of certain attacks such as the "decoy files" [3].

A more effective protection is to compare the hash of the blocks of the file while the download is in progress. Merkle hash trees [9] provide a solution of this sort. An alternative hash scheme is also possible that is more suitable for our protocol. In this alternative scheme, the hash of a file is computed in two stages: First, the file is divided into segments of a certain size and the hash of each segment is computed separately; then the hash of the file is computed as the hash of these segment hashes. The only computational overhead of this method is the extra hash computation over the segment hashes, which would be insignificant given that the segments sizes are reasonably large. We believe that a segment size in the 100KB–1MB range is a reasonable choice for most P2P networks.

Our trust evaluation protocol can be made to work with this new hashing scheme by a simple modification: Once the file version for download is selected, the querier contacts one of the peers who provided the selected hash and requests the detailed hash of the file. Upon receiving the response and verifying its correctness, the peer proceeds to download the file, possibly from multiple sources. During the download, the hash is checked after every downloaded segment and the connection is canceled if a mismatch occurs.

Note that if an attacker sends the fake segment later in the download to delay detection, the benign segments downloaded until that point can be used without any problem, saving the time and bandwidth spent.

4.4 The Problem of Free Riders

A problem with a quite different theme but which may nevertheless benefit from our architecture is the problem of "free riders"; that is, the peers who use the P2P system only to download content but do not serve to other peers. Many users of Kazaa-like file sharing systems use the system as free riders. To tackle this problem and to discourage free riding, some systems determine the priority of the service reception of a peer according to the amount of service the peer has provided in the past. However, this service information is typically provided by the software of the client peer, which is easily hacked to always send the highest possible value. Alternatively, centralized solutions have been proposed where a server is used to keep track of the amount of service provided and received by each peer (e.g., [4, 7]); but this may not be a possible option for the P2P systems that are totally decentralized.

Our trust record system provides a natural distributed infrastructure that can also be used to assess the service level of a peer: At the time of a download, the priority of the download is determined according to the number of 1s in the trust vector the server peer maintains for the client peer. When the local information is insufficient, a trust query can be issued and a "service score" can be calculated from some top few responses. Here, unlike in the trust score calculation, the ranking of the responses should not be based solely on the credibility of the sources—the most credible respondents may possibly have not received any service from the client peer. Instead, a combination of the credibility ratings and the provided service scores should be used.

5 Simulation Experiments

We tested the performance of our protocol with simulations on various attack scenarios. Although it is not possible to exhaust all potential attack types, testing the protocol with a variety of attacks gives an idea on the effectiveness of the protocol. The types of attackers considered in the simulations are,

- *naive,* who responds to every query with a malicious version of the requested file
- *hypocritical,* who acts like a reliable peer most of the time but occasionally tries to send a malicious file
- *collaborative,* who collaborate with each other in trust queries, expressing a positive opinion for malicious peers and a negative opinion for others
- *pseudospoofing,* who change their pseudonym periodically to escape recognition—these attackers are the hardest to detect and their prevention is possible only after honest peers build a sufficient level of trust among themselves
- *pseudospoofing with collaborators,* where the pseudospoofing peers are supported by a group of "collaborators" who normally act as trustworthy peers and build trust in their communities, but give their strongest support to their malicious peers when they receive a relevant trust query.[9]

The simulated P2P networks operate with a Gnutella-like decentralized routing structure. Every peer is linked to a certain number of neighbors, and a query

[9]This attack scenario is more meaningful then collaborators alone, since for malicious support in trust queries to be effective, the peer to receive the support must have a clean history in its neighborhood, hence must be changing its identity periodically. Otherwise, that peer would have been identified as malicious and the support to be given in trust queries would be irrelevant, as observed in Figure 5.

message issued by a peer is propagated over these links for a certain number of hops specified by the TTL. The simulations are run with the following common parameters:

number of peers:	1000
number of distinct files:	1000
number of files each peer initially holds:	10
number of links per peer:	3
TTL:	3
ratio of malicious peers:	1–10%
length of trust vector:	8 bits

Here, the number of peers and files in the network are determined according to the capacity of our system. The number of connections per peer and the TTL are chosen to make the area covered by a peer's reachable neighborhood a reasonable fraction of the whole network—about 2% in this case. 10% malicious ratio represents a high concentration of malicious peers, whereas 1% is the scenario that is probably closer to a real-life situation.

In a simulation run, regular users make file requests periodically, according to a uniform distribution. If the requested file is available locally, no further action is taken. Otherwise, a resource query message is issued, and the protocol proceeds as described in Section 2. Malicious peers may also issue file queries, basically for obtaining genuine files to be used for confidence building. Malicious peers are limited to their databases to send genuine file responses, but they are free to respond to any query maliciously.

It has been observed that the user behavior in P2P file sharing systems show a Zipf-like distribution where users can be grouped into several categories according to their interests, and within each category there are a few highly popular files along with a large number of less popular ones [8]. Our simulations can be expected to give better results when run with a Zipf distribution since positive correlation among users' behavior would result in a more rapid trust establishment among the users in the same category. We preferred to stick to the uniform distribution which favors our protocol the least, since the file requests in a uniform distribution can come from anywhere in the domain and in our system it is only the attackers who are able to respond to all queries unrestrictedly.

5.1 Simulation Results

Results of our simulations are shown in Figures 4–8, where the metrics used to evaluate the performance are:

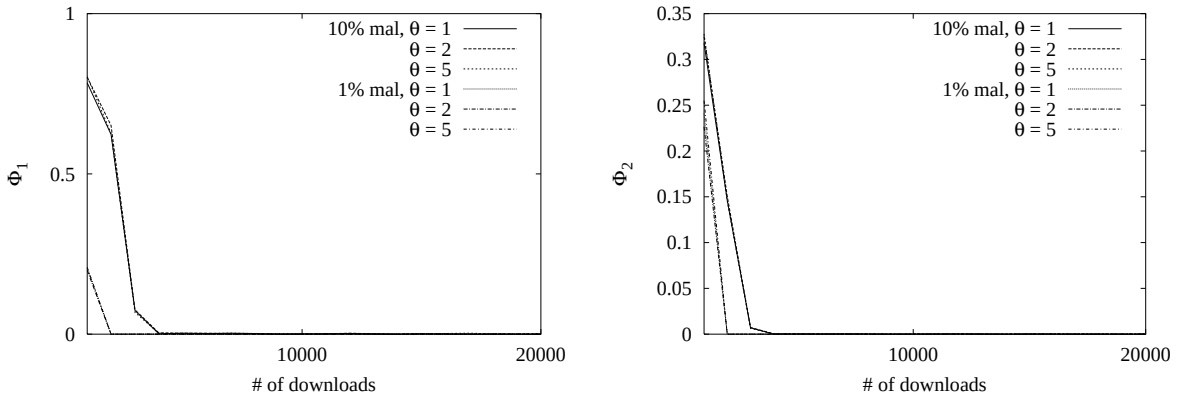
> Φ_1: Ratio of malicious downloads among all downloads
>
> Φ_2: Success ratio of malicious attempts (i.e., the ratio of malicious downloads to malicious responses given)

In the figures, every point shows the value of the statistics measured since the last plotted point (i.e., not cumulative), and the progress of the system is shown in terms of the total number of file downloads.

Throughout the simulations, we take $\theta_T = \theta_C$, denoted by θ. The *inter-query time*, or *iqt*, is the average time between two consecutive file queries of a peer and is used as the basic unit of the simulation time.

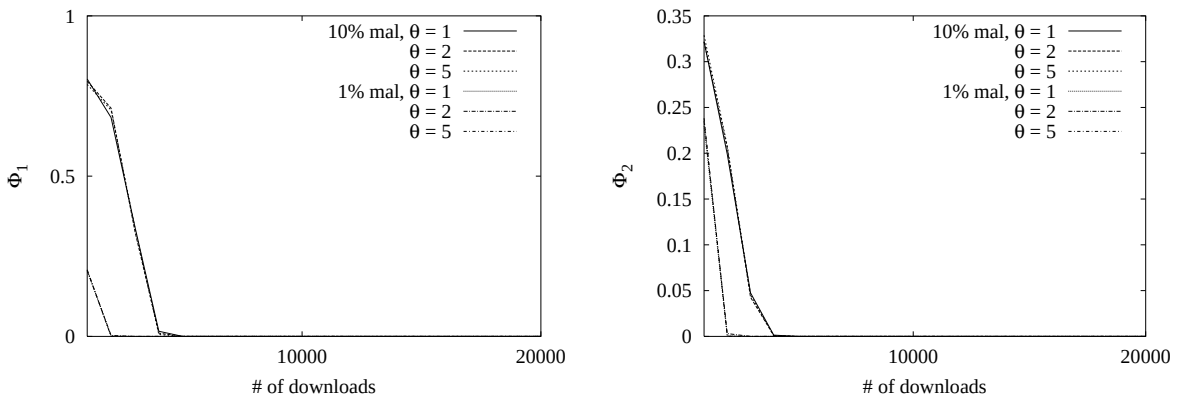
The main characteristics demonstrated by the experiments can be summarized as follows:

- The protocol is quite effective in preventing the malicious downloads and can reduce the attacks' effectiveness to zero within a short time depending on the sophistication of the attackers.
- A large degree of protection can be obtained by just evaluating one most trusted response, i.e., $\theta = 1$. Setting $\theta = 2$ helps against sophisticated attackers. The gain from $\theta > 2$ appears to be negligible.
- The protocol is similarly effective for both 1% and 10% malicious peer density.



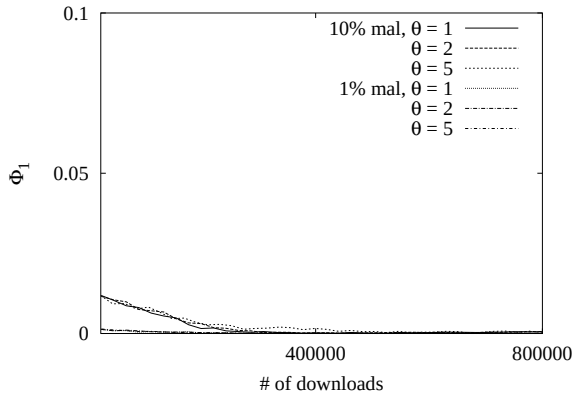
(a) Φ_1 **(b)** Φ_2

Figure 4: Simulation results for the naive attacker type. The attackers are identified and inhibited rapidly. The performance does not depend on θ.

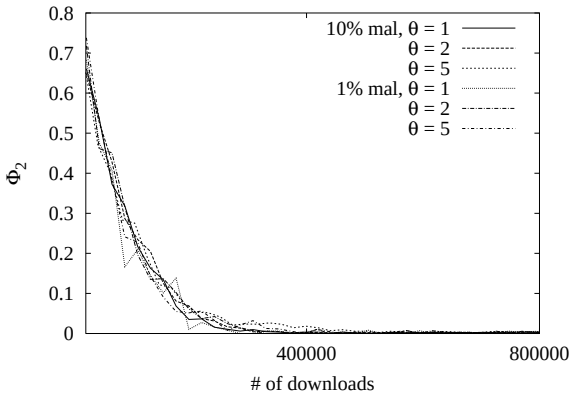


(a) Φ_1 **(b)** Φ_2

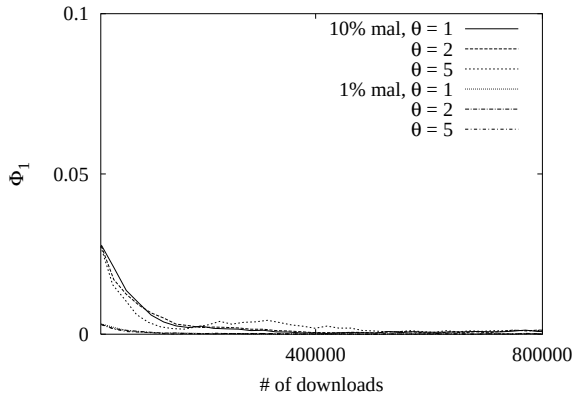
Figure 5: Simulation results for the collaborator attacker type. Their performance is only marginally better than the naive attackers for reasons discussed earlier in this section. (That is, for the support to be given in trust queries to be effective, the peer to receive the support must have a clean history.) A more effective attack scenario can be seen in Figure 8 where collaboration is carried out in coordination with pseudospoofing.



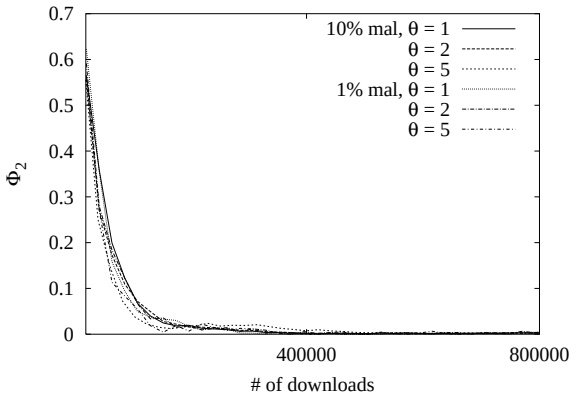
(a) Φ_1, for $\Psi = 0.1$.



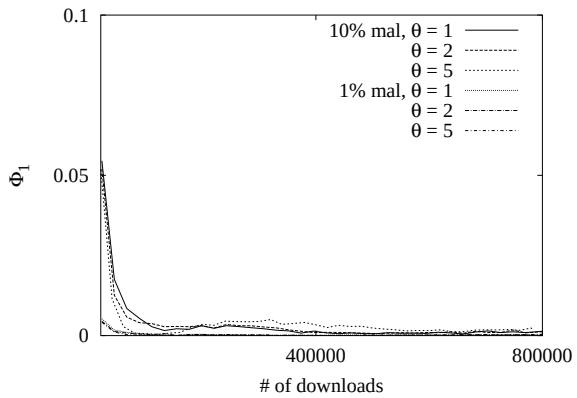
(b) Φ_2, for $\Psi = 0.1$.



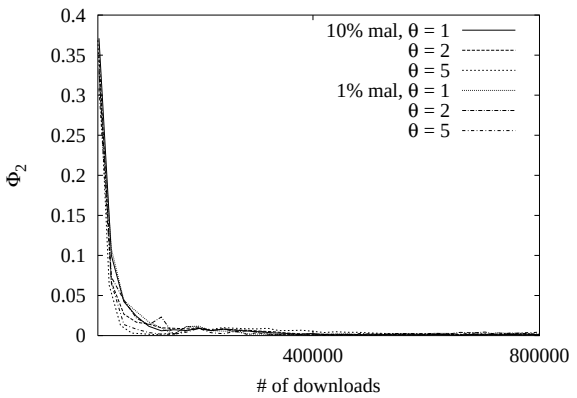
(c) Φ_1, for $\Psi = 0.25$.



(d) Φ_2, for $\Psi = 0.25$.

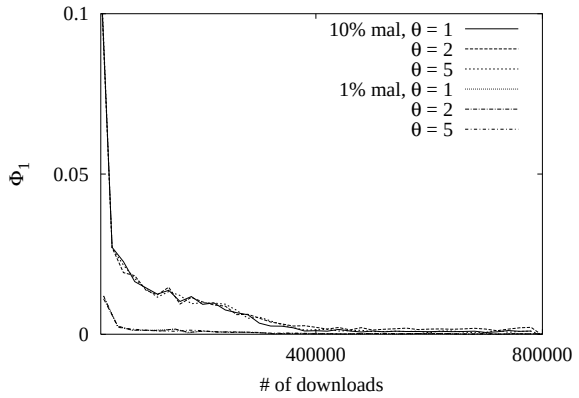


(e) Φ_1, for $\Psi = 0.5$.

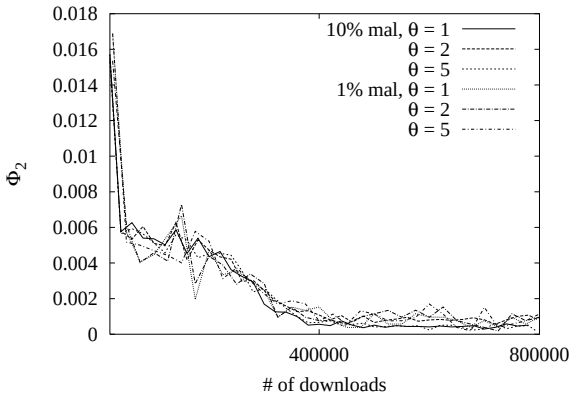


(f) Φ_2, for $\Psi = 0.5$.

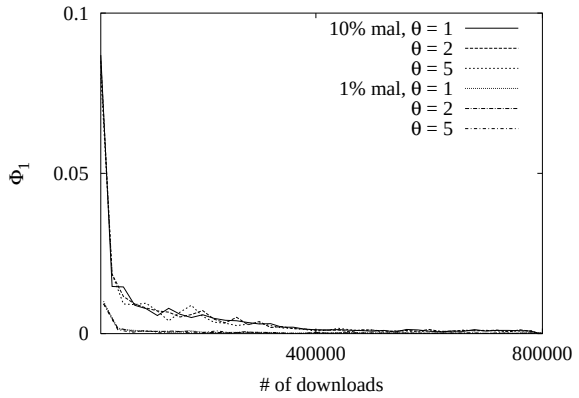
Figure 6: Simulation results for the hypocritical attackers who try to send a malicious file after a certain number of honest uploads. The parameter Ψ specifies the dishonesty rate of the attackers. (E.g., for $\Psi = 0.1$, an attacker tries to send a malicious file after every nine honest uploads.) The results show that detection of the hypocritical attackers take longer than other attacker types, but their level of effectiveness is also significantly lower. Among the Ψ values tested, the best attack performance is obtained for $\Psi = 0.5$



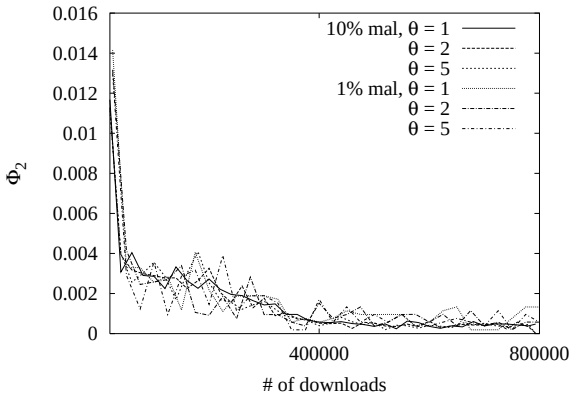
(a) Φ_1, for $p = 50$.



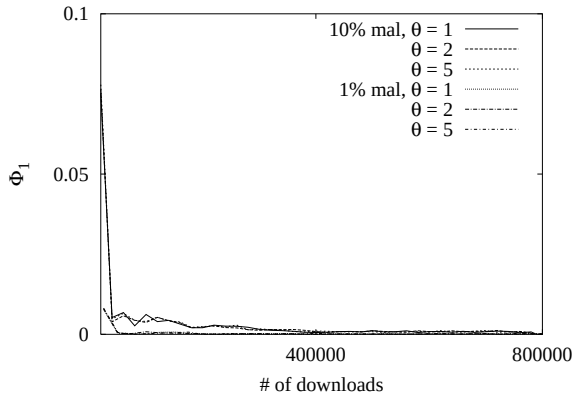
(b) Φ_2, for $p = 50$.



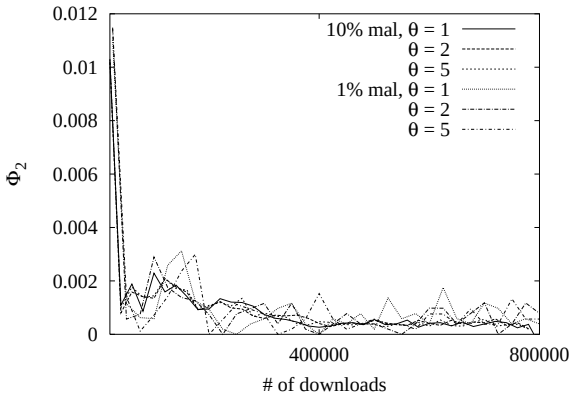
(c) Φ_1, for $p = 100$.



(d) Φ_2, for $p = 100$.

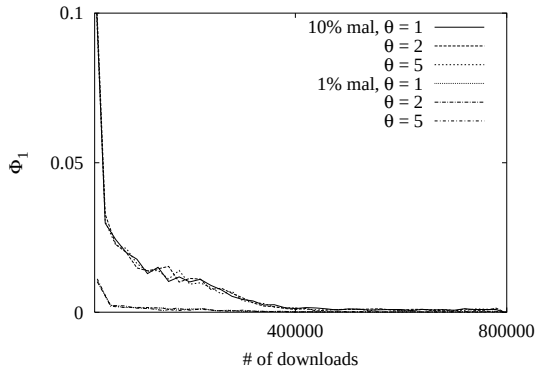


(e) Φ_1, for $p = 200$.

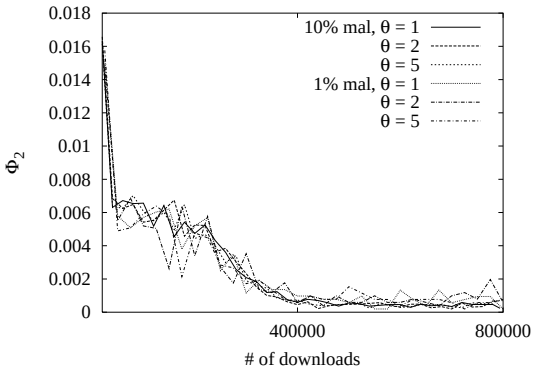


(f) Φ_2, for $p = 200$.

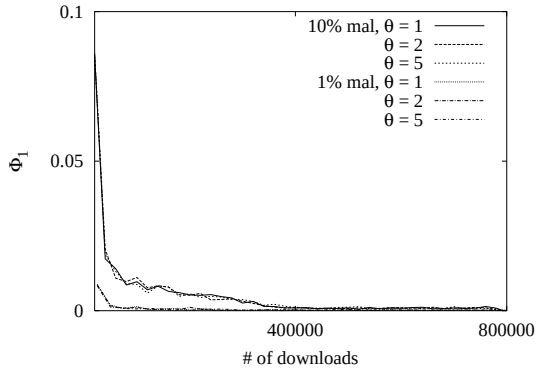
Figure 7: Simulation results for the pseudospoofing attackers who adopt a new identity periodically. The parameter p specifies the period of the identity change. (E.g., for $p = 100$, an attacker adopts a new identity at every 100 iqt.) This attacker type is the hardest to detect and prevent. Nevertheless, their ability to spread malicious content converges to zero as good peers get to know each other and build trust among themselves.



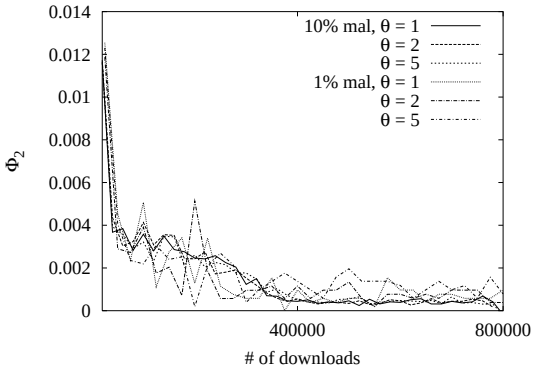
(a) Φ_1, for $p = 50$.



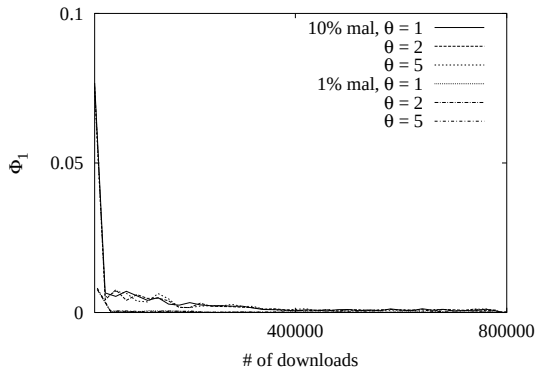
(b) Φ_2, for $p = 50$.



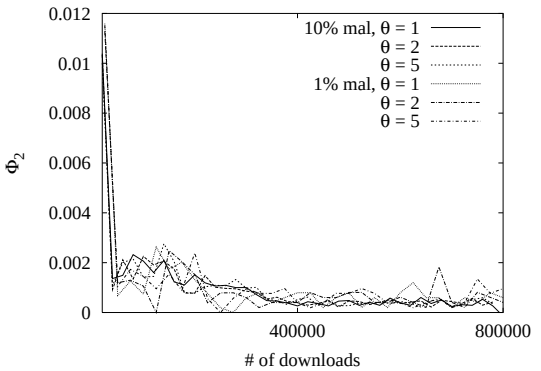
(c) Φ_1, for $p = 100$.



(d) Φ_2, for $p = 100$.



(e) Φ_1, for $p = 200$.



(f) Φ_2, for $p = 200$.

Figure 8: Simulation results for the pseudospoofing attackers with collaborators. Here, 1–10% pseudospoofing malicious peers try to spread malicious content where another 10% of the peers are *collaborators* who normally act as trustworthy peers and build confidence in their communities, but give their full support to the pseudospoofing malicious peers in trust queries—the 10% collaborator ratio, which is probably too high to be realistic, is chosen to guarantee the presence of at least one collaborator in the neighborhood of every pseudospoofing attacker in order to make the attacks more effective. This attack type is somewhat more effective than pseudospoofing alone, but their effectiveness also converge to zero as good peers build trust with each other.

6 Comparison to Related Earlier Work

A number of protocols have been proposed recently for reputation-based trust management in P2P systems. In this section, we discuss them briefly in comparison to our protocol.

One of the earliest works in this area is the protocol by Aberer and Despotovic [1] which aims to identify dishonest peers by a complaint-based system. A shortcoming of this protocol is that it maintains only the negative feedbacks, providing no means for a trustworthy peer to be distinguished from a newcomer. The trust evaluation is also rather simplistic, classifying every peer either as trustworthy or untrustworthy. Moreover, maintenance of a "P-Grid" architecture is required on top of the existing P2P structure.

A more interesting protocol is the EigenTrust scheme proposed by Kamvar et al. [8], which is based on evaluating the trust information provided by the peers according to their trustworthiness (i.e., using the trust ratings for credibility). The evaluation process is based on a rather interesting normalization assumption: The trust ratings held by a peer are normalized such that their sum equals 1. Although this normalization has interesting properties mathematically—the resulting trust matrix becomes a Markov matrix and the global trust rating computation converges to the principal eigenvector of that matrix (hence the name EigenTrust)—it has less desirable consequences securitywise: By this normalization, significant trust information is lost: E.g., if there are n identical trust ratings in the database, the normalized value of them will be $1/n$ whether the original values were the highest possible ratings or the lowest; or, a single non-zero rating in the database will always be normalized to 1, regardless of its value.

A protocol that specifically addresses the issue of computing a trust score for the alternative file versions obtained in a query is described in a recent paper by Damiani et al. [5]. Although similar to our proposal in scope, this protocol is different in some major aspects:

- The protocol goes through four phases of message exchanges before the download can start: Resource query, voting (similar to our trust query), verification of the votes, verification of the hash of the file selected for download.
- The voting and vote verification protocols have no cryptographic authentication and relies on the IP addresses for the messages' authenticity, making them vulnerable to active attacks.
- The votes are evaluated without any consideration of the credibility or trustworthiness of the voters.
- No quantitative trust metric is specified to be used for choosing among alternative files for download.

An important contribution of [5] is the idea of maintaining reputations for resources as well as for peers, which we discussed in Section 7.

A study with a rather different but nevertheless relevant scope is a recent paper of Xiong and Liu [12] on trust evaluation in P2P e-commerce communities. The paper emphasizes two points for P2P reputation systems:

- In a rating scheme, the complaints, or any other opinions for that matter, should be evaluated according to the credibility of their providers.
- A peer's behavior in different contexts should be evaluated differently. (E.g., feedbacks from small and large transactions should be weighted differently, according to the size of the transaction.)

The paper does not deal with the specifics of the functions and protocols for trust evaluation. However, they do simulations with an experimental rating scheme modified from the scheme in [1] based on P-Grids.

7 Final Considerations

Improvements are possible on the basic protocol to make it more efficient. For example, a timer mechanism can be used to detect and remove the trust vectors belonging to peers that are no longer active. Trust queries can be made more efficient by combining all IDs to be queried into a single query message, reducing the number of query and response messages to be handled.

Although the protocol maintains ℓ-bit trust and credibility vectors, it might be more suitable to use only part of that information for different purposes. For example, when evaluating trust responses that come from peers, it may be more desirable to take only the most recent few transactions into account.

A potential improvement on the basic protocol may be realized by preserving the hashes of the malicious files downloaded. These hashes can later be used to send a warning to the querying peer when a relevant query is received. This idea was originally proposed in [5] in a similar context. Our protocol can be enhanced to include this feature with the following modifications: The warning messages received in a query are grouped along with the normal responses according to their file hash value. If selected into the top θ_T for trust evaluation, a warning message's trust and

distrust ratings are reversed in the trust score calculation, contributing a significant distrust factor to the average.

The limitations of our protocol must also be noted. Being a reputation-based protocol, our system in the end relies on the judgment of its users. Therefore, it can be effective only against attacks that are discernible by the user. Nevertheless, many attacks in P2P systems fall into this category, such as the common decoy files attacks [3].

Another point to note is that our protocol does not distinguish between malicious peers and the peers that spread malicious content due to their carelessness, which we believe is the right way to deal with careless peers from a practical point of view. Besides, a careless peer always has the ability to improve its reputation by serving a sufficient number of good files once it corrects its attitude.

Our protocol is designed to be compatible with most first generation P2P systems. However, certain optimizations would be needed to obtain the best performance when integrating it with a specific system. For example, in a Gnutella-like network where a peer's connections are changed constantly to provide rapid distribution of the content across the network, building a reliable reputation base can take too long and a malicious peer can escape recognition for a long time due to the constantly changing neighborhood. In such a system, a connection scheme where some of the neighbors of a peer change continually for content distribution and others, which are possibly determined by a longest prefix match on the ID, remain relatively stable for trust management, could be more effective for faster trust establishment. More detailed simulations that consider this kind of specifics of the network where the protocol is to be deployed, and with a more sophisticated modeling of the attackers according to the network's possible vulnerabilities, would be needed to get a more realistic evaluation of the proposed architecture for deployment in an actual system.

Acknowledgments

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