X-Vine: Secure and Pseudonymous Routing Using Social Networks

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Abstract

Distributed hash tables suffer from several security and privacy vulnerabilities, including the problem of Sybil attacks. Existing social network-based solutions to mitigate the Sybil attacks in DHT routing have a high state requirement and do not provide an adequate level of privacy. For instance, such techniques require a user to reveal their social network contacts. We design X-Vine, a protection mechanism for distributed hash tables that operates entirely by communicating over social network links. As with traditional peer-to-peer systems, X-Vine provides robustness, scalability, and a platform for innovation. The use of social network links for communication helps protect participant privacy and adds a new dimension of trust absent from previous designs. X-Vine is resilient to denial of service via Sybil attacks, and in fact is the first Sybil defense that requires only a logarithmic amount of state per node, making it suitable for large-scale and dynamic settings. X-Vine also helps protect the privacy of users social network contacts and keeps their IP addresses hidden from those outside of their social circle, providing a basis for pseudonymous communication. We first evaluate our design with analysis and simulations, using several real world large-scale social networking topologies. We show that the constraints of X-Vine allow the insertion of only a logarithmic number of Sybil identities per attack edge; we show this mitigates the impact of malicious attacks while not affecting the performance of honest nodes. Moreover, our algorithms are efficient, maintain low stretch, and avoid hot spots in the network. We validate our design with a PlanetLab implementation and a Facebook plugin.

1 Introduction

Peer-to-peer (P2P) networks have, in a short time, revolutionized communication on the Internet. One key feature of P2P networks is their ability to scale to millions of users without requiring any centralized infrastructure support. The best scalability and performance is offered by multi-hop distributed hash tables (DHTs), which offer a structured approach to organizing peers [37, 52, 56, 59]. Multi-hop DHTs are the subject of much research and are also used in several mainstream systems [2, 7, 25].

Securing DHTs has always been a challenging task [16, 57, 63], especially in the face of a Sybil attack [22], where one node can pretend to have multiple identities and thus interfere with routing operations. Traditional solutions to this attack require participants to obtain certificates [16], prove possession of a unique IP address [43, 46], or perform some computation [12]. This creates a barrier to participation, limiting the growth of the P2P user base, and at the same time does not fully address the problem of Sybil attacks.

To address this, recent research proposes to use social network trust relationships to mitigate Sybil attacks [21, 68, 69]. However, these systems share some key shortcomings:

High control overhead: These systems rely on flooding or large numbers of repeated lookups to maintain state. For example, Whanau [34] is the state-of-art design that secures routing in DHTs, but it is built upon a *one-hop* DHT routing mechanism, and has high overheads: state and control overhead increases with $O(\sqrt{n}\log n)$, where n is the number of participants in the social network. As networked systems become increasingly deployed at scale (e.g., in the wide area, across service providers), in high-churn environments (e.g., developing regions, wireless, mobile social networks [40]), and for applications with stronger demands on correctness and availability (e.g., online storage, content voting, reputation systems) the problem of high overhead in existing works stands to become increasingly serious; multi-hop DHT routing mechanisms are going to be necessary.

Lack of privacy: These systems require a user to reveal social contact information (friend lists). Some of these schemes require global distribution of this contact information. This is unfortunate, as social contacts are considered to be private information: leading real-world systems like Facebook [3] and LiveJournal [4] provide users with a functionality to limit access to this information. Forcing users to reveal this private information could greatly hinder the adoption of these technologies.

A second privacy concern, common to both traditional DHTs and ones that use social networking information, is that users must communicate directly with random peers, revealing their IP addresses. This provides an opportunity for the attacker to perform traffic analysis and compromise user privacy [9, 35]. Prior work [42, 65]has demonstrated that a colluding adversary can associate a DHT lookup with its lookup initiator, and thus infer the activities of a user. A *pseudonymous* routing mechanism can defend against such attacks, and would be especially beneficial for privacy sensitive DHT applications [19, 43].

To address these shortcomings, we propose X-Vine, a protection mechanism for large-scale distributed systems that leverages social network trust relationships. X-Vine has several unique properties. X-Vine protects *privacy* of social relationships, by ensuring that a user's relationship information is revealed only to the user's immediate friends. At the same time, X-Vine also protects *correctness* of DHT routing, by mitigating Sybil attacks while requiring only logarithmic state and control overhead. To the best of our knowledge, X-Vine is the first system to provide both properties, which may serve to make it a useful building block in constructing the next generation of social network based distributed systems. Finally, X-Vine also provides a basis for pseudonymous communication; a user's IP address is revealed only to his/her trusted social network contacts.

X-Vine achieves these properties by incorporating social network trust relationships in the DHT design. Unlike traditional DHTs, which route directly between overlay participants (e.g., [34]), X-Vine embeds the DHT directly into the social fabric, allowing communication through the DHT to leverage trust relationships implied by social network links. This is done by using mechanisms similar to network layer DHTs like VRR [14]. We leverage this structure for two purposes. First, communication in X-Vine is carried out entirely across social-network links.The use of social network links enables pseudonymous communication; while the recipient may know the opaque identifier (pseudonym) for the source, the IP address of the source is revealed only to his/her friends. Second, recent work has shown that social networks can be used to detect Sybil attacks by identifying a bottleneck cut that connects the Sybil identities to the rest of the network [21, 68, 69]. X-Vine enables comparable Sybil resilience by bounding the number of DHT relationships that can traverse a particular edge. With this multi-hop approach, we can limit the number of Sybil identities per attack edge (attack edges illustrated in Figure 1) to logarithmic in the size of the network with logarithmic control and routing state, a dramatic reduction from previous Sybil defense approaches. This allows X-Vine to scale to large user bases and high-churn environments.

We evaluate X-Vine both analytically and experimentally using large scale real-world social network topologies. Since recent work [62, 66] has advocated the use of interaction networks as a more secure realization of social trust, we also demonstrate the performance of X-Vine on interaction graphs. From our evaluation, we find that X-Vine is able to route using 10–15 hops (comparable to other DHTs) in topologies with 100 000 nodes while using only $O(\log n)$ routing state. In particular, we show that the overhead of X-Vine is two orders of magnitude smaller than Whanau. With respect to Sybil resistance, we found that honest nodes are able to securely route to each other with probability greater than 0.98 as long as the number of attack edges is $g \in o(n/(\log n))$. Using an implementation on PlanetLab, we estimate the median lookup latency in a 100 000 node topology to be less than 1.2 seconds. Even when 20% of the nodes fail simultaneously, the lookups still succeed with a probability greater than 95%. Finally, we also implement a plugin for DHT designers that can enable them to easily integrate social network contacts with a DHT by leveraging existing online social networks like Facebook.

Our proposed techniques can be applied in a wide variety of scenarios that leverage DHTs:

- Large scale P2P networks like Vuze/Kad/Overnet are popularly used for file sharing and content distribution. However, these networks are vulnerable to attacks on the routing protocol [64] and do not protect the privacy of the user [42]. X-Vine protects against attacks that target the DHT mechanisms and provides a basis for pseudonymous communication. Moreover, X-Vine is also robust to the high churn prevalent in these networks.

- Applications like Coral [25], Adeona [54], and Vanish [27] are built on top of DHTs. The security properties of these applications can often be compromised by exploiting vulnerabilities in the DHT. As an example, the security of Vanish was recently compromised by a low-cost Sybil attack on the Vuze network [67]. Our proposed techniques protect these applications by bounding the number of Sybil identities in the DHT.

- Decentralized P2P anonymous communication systems like Tarzan [26], Salsa [46] and ShadowWalker [43] assume an external Sybil defense mechanism. X-Vine is particularly suitable for designing Sybil-resilient P2P anonymous communication systems, since it provides secure as well as pseudonymous routing.

- Freenet [19] is a widely used censorship resistant overlay network, but its routing algorithm has been shown to be extremely vulnerable in presence of even a few malicious nodes [23]. X-Vine can enable peers to resist censorship by securely and pseudonymously retrieving data objects from the Freenet network.

- Membership concealing overlay networks (MCONs) [61] hide the identities of the peers participating in a network (different from pseudonymity). Our proposed techniques can provide a substrate for designing fully decentralized membership concealing networks.

Roadmap: The rest of the paper describes and evaluates X-Vine. We start by giving a high-level overview of the problem we address and our approach (Section 2), followed by a detailed description of our routing algorithm (Section 3) and its security mechanisms (Section 4). We then describe our experimental results (Section 5). Finally, we summarize related work (Section 6), discuss X-Vine's limitations (Section 7), and conclude (Section 8).

2 X-Vine Overview

2.1 Design Goals

We start by defining the goals for our design.

1. Secure routing: if an honest node X performs a lookup for an identifier ID, then the lookup mechanism must return the global successor of ID (present in the routing tables of honest nodes).
2. Pseudonymous communication: an adversary should not be able to determine the IP address corresponding to a user.
3. Privacy of user relationships: an adversary should not be able to infer a user's social contacts.
4. Low control overhead: the control overhead of the system should be small to enable a scalable design. This excludes flooding-based and single-hop mechanisms.
5. Low latency: the length of the path used to route to an arbitrary identifier should be small, in order to minimize lookup latency.
6. Churn resilience: even when a significant fraction of nodes fail simultaneously, lookup queries should still succeed.
7. Fully decentralized design: we target a fully decentralized architecture without any central points of trust/failure.

We note that requirements 2, 3 and 4 distinguish us from prior work—state-of-the-art approaches do not provide pseudonymous routing, do not preserve privacy of user relationships, and have high control overhead.

2.2 Threat Model and Assumptions

We assume that a fraction of real users are compromised and colluding. Recent work [21,68,69] has leveraged the insight that it is costly for an attacker to establish many trust relationships. Following this reasoning, we assume that the number of attack edges, denoted by g, is bounded. Similar to prior work, we assume that the attack edges are not specially chosen.

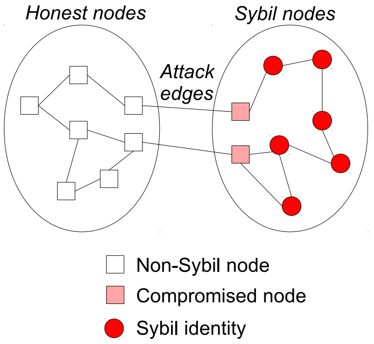


Figure 1. Illustration of honest nodes, Sybil nodes, and attack edges between them.

Recent work has challenged the assumption that it is costly for an attacker to create attack edges with honest nodes in friendship graphs [10, 13, 29, 66], and proposed the use of interaction graphs as a more secure realization of real world social trust. In this work, we will evaluate X-Vine with both traditional friendship graphs as well as topologies based on interaction graphs. Other mechanisms to infer the strength of ties between user [28] may also be helpful in creating resilient social graphs, but are not the focus of this paper.

We also assume that the set of colluding compromised nodes is a Byzantine adversary, and can deviate from the protocol in arbitrary ways by launching active attacks on the routing protocol. In particular, the set of compromised nodes can launch a Sybil attack by trying to insert multiple fake identities in the system. The key assumption we make about the adversary is that Sybil identities are distributed randomly in the DHT identifier space. We note that this assumption is a limitation of the X-Vine protocol, as discussed in Section 7. An exploration of defenses against adversaries who concentrate their nodes in a particular region of the overlay is beyond the scope of this paper.

2.3 Solution Overview

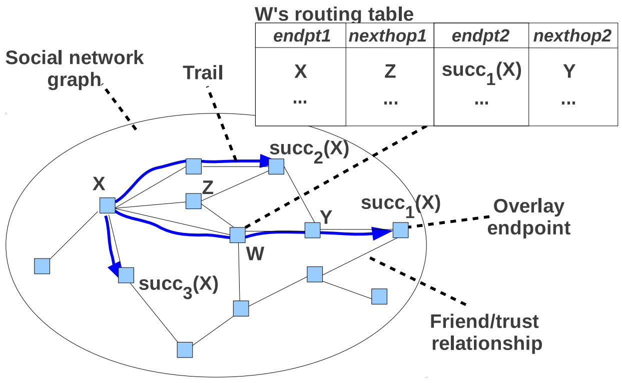
We start by describing our algorithm in the context of an abstract, static network. Suppose we have a graph G, where nodes correspond to users of the social network, and edges correspond to social relationships between them. Our approach runs a DHT-based routing scheme over the graph that embeds path information in the network. We first describe how routing is performed, and then describe how the path information it creates can be used to mitigate Sybil attackers.

Pseudonymous routing in the social network: We construct a DHT on top of the social network, using mechanisms similar to network layer DHTs [14]. Each node in the network selects a random numeric identifier, and maintains paths (*trails*) to its neighbors in the identifier space in a DHT-like fashion. To join the network, a node performs a discovery process to determine a path to its *successors* in the DHT. Then, the node embeds trails in the network that point back to the joining node's identifier. To route messages, packets are forwarded along these trails. By maintaining trails to each of the node's successors, a node can forward a message to any point in the namespace. Users that are directly connected by a social network link simply communicate via the IP layer. All communication performed by a node is done only with its friends, and this communication is done in a manner that does not reveal the node's local topology, preventing leakage of friendship list information to non-friends. Routing over social links also enables a user to communicate pseudonymous with respect to non-friends.

Protecting against Sybils: The scheme described above does not mitigate the Sybil attack, as a malicious node can repeatedly join with different identifiers, and thereby "take over" a large portion of the identifier space. Malicious nodes can in fact pretend that there is an entire network of Sybil nodes behind themselves (Figure 1). To protect against the Sybil attack, we constrain the number of paths between honest nodes and malicious nodes. Since Sybil nodes by their very nature are likely to be behind a small "cut" in the graph, by constraining the number of paths that may be set up, we can constrain the impact that a Sybil node can have on the entire network. In particular, honest nodes rate-limit the number of paths that are allowed to be constructed over their adjacent links, thereby limiting the ability of Sybil nodes to join the routing scheme, and hence participate in the network. When a joining node attempts to establish a trail over an edge that has reached its limit, the node adjacent to the full link sends the joining node a message indicating failure of the join request. This limits Sybil nodes from constructing very many paths into the network. Since Sybil nodes cannot construct many trails, they cannot place many identifiers into the DHT. Hence, an honest node can send traffic to another honest node by forwarding traffic over the DHT, as trails are unlikely to traverse Sybil-generated regions of the network.

3 X-Vine Protocol

The key feature of our design is that all DHT communication happens over social network links.[1] By ensuring that all communication takes place over social network links, we can leverage the trust relationships in the social network topology to enforce security properties. A trivial security property of our design is that an adversary needs to be connected to honest users via a series of social network links to communicate with them. Moreover, the IP address of the nodes only needs to be revealed to their contacts, enhancing privacy for users. Most importantly, our design is able to effectively resist Sybil attacks even when the number of attack edges is large.



W's routing table

endpt1	nexthop1	endpt2	nexthop2
X	Z	$succ_1(X)$	Y
...	...	...	...

Figure 2. Overview of X-Vine.

3.1 Routing Over Social Networks

Figure 2 illustrates the design of X-Vine. Our design uses a VRR-like [14] protocol to construct and maintain state at the overlay layer. Here, we first describe the state maintained by each node, and then describe how that state is constructed and maintained over time.

State maintained by each node: X-Vine constructs a *social overlay* on top of the social network, where a node has direct links to friends, but also maintains "overlay links" to remote nodes. These remote nodes (*overlay endpoints*) are selected in a manner similar to Chord [59]: each node is assigned an identifier from a ring namespace, and forms overlay links to nodes that are successors (immediately adjacent in the namespace), and (optionally) fingers (spaced exponentially around the ring). Unlike Chord however, a node is not allowed to directly send packets to its overlay neighbor: for security reasons, nodes only receive packets from their social network links. Hence, to forward a packet from a node to one of its overlay endpoints, the packet will have to traverse a *path* in the social network graph. To achieve this, corresponding to each of its overlay endpoints, a node maintains a *trail* through the social network. Each node along the trail locally stores a *record* consisting of four fields: the identifiers of the two endpoints of the trail, and the IP addresses of the next and previous hops along the trail. Using this information, a node can send a packet to its endpoints,

[1] Applications such as Vuze may optionally choose to benefit only from X-Vine's Sybil resilience, and can forgo pseudonymity by directly transferring files between overlay nodes after the lookup operation.

by handing the packet off to the first node along the trail, which looks up the next hop along the trail using its trail records, and so on. Furthermore, using a Chord-like routing algorithm, a node can route to any other node in the namespace, by (upon reaching an endpoint) selecting the next overlay hop that maximizes namespace progress to the destination (without overshooting). As an optimization, instead of waiting until the endpoint is reached to determine the next overlay hop, intermediate nodes along the path may "*shortcut*" by scanning all their trail records, and choosing the endpoint that maximizes progress in the namespace (see Algorithm 1 in Appendix B). If the intermediate node discovers an endpoint that makes more namespace progress to the destination than the current next overlay hop, the intermediate node may choose to forward the packet towards this new endpoint, to speed its progress (while explicitly maintaining the next overlay hop in the packet is not strictly necessary for routing, we do so to simplify parts of our design described later).

State construction and maintenance: Since nodes can route, we can perform other DHT operations by simply performing routing atop this structure. For example, we can execute a Chord-like join: upon arriving at the network, a node can route a *join request* towards its own identifier, and the node that receives it can return back the identifiers which should be the joining node's successors. However, there are two key changes we need to make. First, when a node initially arrives, it does not yet have any trail state and hence cannot forward packets. To address this, the joining node randomly selects one of its friends in the social network to act as a *bootstrap* node. The joining node sends its join request using the bootstrap node as a proxy. Second, the joining node also needs to build trails to each of its endpoints (e.g., its successors). To do this, for each endpoint, it sends a *trail construction request* to the identifier of that endpoint. As the request is routed, each intermediate node along the path locally stores a record corresponding to the trail. Finally, when these steps are completed, the joining node can route to any node in the network (by forwarding packets through its endpoints), and it can receive packets from any node in the network (by accepting packets through its endpoints). To maintain this state, we need to achieve two things. First, we would like to correctly maintain the set of records along each trail in the presence of churn, so each node can reach the trail endpoint. This is done in a manner similar to AODV [49]: each node along the path locally probes its neighbors and removes trail records (sending *teardown* messages upstream if necessary) corresponding to failed trails. Second, we would like to make sure each trail points to the corresponding globally correct successor/finger. To do this, we leverage the stabilization mechanisms from Chord and VRR [14, 59].

3.2 Balancing Routing State

Temporal correlation: while the scheme above is correct, it performs poorly in practice. The reason for this is due to *temporal correlation*—since trails are constructed using other trails, social network links that are initially chosen to be part of a trail become increasingly likely to be part of later trails. Because of this, nodes that join the network early tend to accumulate more state over time. To illustrate this problem, we describe an example. Suppose a node X has d friends $a_1, a_2, .., a_d$. Suppose also that there is a trail from X to Y for which the next hop is node a_d. Next, suppose node X is an intermediate node in a new overlay path that is being setup from node a_1 (which is also the previous hop). With probability $2/d$, the next hop of the overlay path will be a_d. Similarly, in the future, the probability of a_d being chosen as the next hop in an overlay path increases to $3/(d+1)$, and then to $4/(d+2)$, and so on. This example illustrates that a social network link that was initially chosen as part of a trail has an increasing chance of being chosen in trails that are set up in the future. Consequently nodes that join the social network early tend to be part of many trails. This is not desirable from both a security perspective or a performance perspective.

Stabilization algorithms: To address the problem of temporal correlation, we propose two modifications to the core X-Vine algorithms: The first algorithm leverages the social connections of new users to reduce the path lengths of existing trails. When a new node joins the system, its social contacts that are already part of the X-Vine system consider all trails in their routing tables that have a path length greater than a threshold thr_1 (set to the upper quartile of trail path path lengths). Corresponding to each such trail, the social contacts check if modifying the trail via the new node would reduce the path length, and if so, a teardown message is sent to the old trail and another trail via the new node is setup. The threshold on the path length helps to avoid needless communication for trails that are already short, and are thus unlikely to benefit much from new edges in the social graph topology. The second algorithm helps to load balance the routing state at nodes, and also leads to a reduction in the path lengths of trails. This algorithm is run by all nodes whose routing state is greater than a threshold thr_2. Such nodes consider all trails in their routing tables whose path length is greater than a threshold thr_1 (similar to the previous algorithm), and send messages to the overlay end points to check if alternate trails can be established, and if their path length is shorter than the current path length. If a shorter alternate trail exists, then it replaces the existing trail. This helps reduce the routing state size at congested nodes, while simultaneously reducing the trail path lengths.

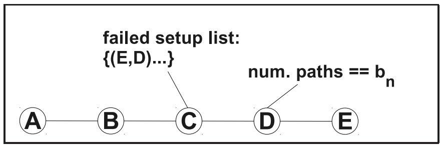


Figure 3. Example: backtracking.

3.3 Bounding State With Local Policies

We have seen that the shortcut-based routing protocol described in Section 3.1 faces the problem of temporal correlation, leading to unbounded growth in routing state. To complement our stabilization algorithms, we propose a mechanism by which nodes can set a hard bound on their routing state size using local routing policies. These policies can be set to account for heterogeneity across nodes, users' desired degree of participation in the network, and to limit the worst-case state overhead at any particular node. Our architecture allows users to set two types of policies pertaining to state maintained at their local node:*Bounding routes per link:* If the number of trails traversing an adjacent social network link reaches a threshold b_l, then the user's node refuses to set up any more trails traversing that link. *Bounding routes per node:* If the number of trails traversing the user's node reaches a threshold value b_n, then the node refuses to set up any more trails via itself. Due to these routing policies, it is possible that a request to set up a trail may be unable to make forward progress in the overlay namespace. To address this, we introduce a technique called *backtracking* that explores alternate social network paths in case an intermediate node refuses to process a path setup request. To do this, each node maintains a *failed setup list*, containing a list of trails that have failed to set up. When a node attempts to set up a trail via a next hop, and receives a *rejection* message indicating that the next hop is full, the node inserts an entry into its failed setup list. Each record in the list contains the identifier of the destination overlay endpoint that the packet was traversing towards, and the identifier of the next hop in the social network that rejected the path setup. When forwarding a message to a particular destination endpoint, a node removes from consideration next hops contained in the failed setup list corresponding to that endpoint (see Algorithm 2 in Appendix B). The failed setup list is periodically garbage collected by discarding entries after a timeout.

For example (Figure 3), suppose node A wishes to establish a path to E, and determines B is the best next overlay hop. A places E into the *next overlay hop* field in the message, and forwards the message to B. Similarly, B forwards the message to C. Suppose D is congested (has more than b_n paths traversing it). In this case, C sends the path setup message to D, but D responds back with a rejection message. C then stores the entry (E, D) in its failed setup list, to indicate that establishing a path via D to reach E was unsuccessful. C then attempts to select an alternate next hop that makes progress in the namespace (either a route to the current next overlay hop, or a "shortcut" route that makes more progress than the current next overlay hop). If C does not have such a route, it sends a rejection message back to B, which inserts the entry (E, C) in its failed setup list. This process repeats until a path is discovered, or a time-to-live (TTL) contained in the packet is exceeded. When the TTL is exceeded, the path setup fails, and the source node must attempt to rejoin to establish the path.

4 Securing X-Vine

The previous section described our approach to perform routing atop the social network. In this section, we describe how to extend and tune the design in the previous section to improve its resilience to attack. We start by providing an overview of attacks on our design(Section 4.1), and then propose extensions to improve resilience to them (Section 4.2).

4.1 Attacks on the Routing Protocol

We investigate defenses to the following attacks on DHTs:

Sybil attack [22]: The attacker can insert a large number of Sybil identities in the DHT, and set up paths with their successors and predecessors. The attack results in honest nodes' routing tables being populated by malicious Sybil identities. This increases the probability that lookup queries will traverse some malicious nodes, which can then drop or misroute the lookup queries. Observe that to minimize resources, it suffices for Sybil identities to maintain paths with only nodes in the predecessor list, since paths to the nodes in the successor list will result in a shortcut to the honest successor nodes.

Attacks on routing table maintenance: In addition to the Sybil attack, the adversary could also manipulate the routing table maintenance protocols to increase the probability of malicious nodes being present in honest nodes' routing tables. *Intercepting trails:* During churn, malicious nodes can become part of a large number of trail paths between nodes, in order to attract lookup traffic (for example, by refusing to send trail teardown messages). *Attacking trail construction:* The attacker could prevent honest nodes from finding a trail path to their correct successor. This could be done by dropping or misrouting the trail setup messages. *Attacks on message integrity:* Malicious nodes that forward control traffic could modify the content of the messages, to disrupt trail setup (for example, by creating routing loops). *Forgery attacks:* The malicious nodes could spoof source identifiers in messages sent to honest nodes (for example, to give the appearance that the message came from the honest node's friends).

Attacks on lookups: Once the attacker is able to intercept a lookup query, it can either drop the packet or misroute it. Such attacks can prevent the honest nodes from either discovering their correct successor in the ring, or discovering a malicious successor list set respectively. By advertising malicious nodes as the successors of an honest joining node, a significant fraction of the honest joining node's traffic would traverse malicious nodes. Note that attacks on both overlay construction and overlay routing are captured by this attack, since in a DHT, both bootstrap and routing are accomplished by the same operation: a lookup.

4.2 Proposed Defenses

We note that it is imperative to secure *both* the routing table maintenance and lookup forwarding. If the routing table maintenance protocol were insecure, then the adversary could manipulate the routing table entries of honest nodes to point to malicious nodes, and routing to honest nodes would not be successful. However, even if the routing table maintenance mechanisms are secure, the adversary still has the opportunity to drop lookup packets or misroute them.

Mitigating the Sybil attack: To limit the impact of the Sybil attack, we propose that nodes implement a routing policy that bounds the number of trails that traverse a social network edge. We denote the bound parameter as b_l. Since the attacker has limited attack edges, this bounds the number of overlay paths between the honest subgraph and the Sybil subgraph *regardless of the attacker strategy*. Thus, we limit the number of Sybil identities that are part of the honest node's routing table. The key challenge in this approach is to determine the bound b_l that enables most honest nodes to set up trails with each other while hindering the ability of Sybil nodes to join the DHT. Our analytic and experimental results suggest that a bound of $b_l \in \Theta(\log n)$ works quite well. Similar to Yu et al. [68], we assume that the bound b_l is a system wide constant known to all honest nodes. Honest nodes are able to set up trails with each other even though there is a bound on the number of trails per social network link because of the fast-mixing nature of the social network. On the other hand, a Sybil attack gives rise to a sparse cut in the social network topology, and we use this sparse cut to limit the impact of the Sybil identities. The number of overlay paths between the honest and Sybil subgraphs is bounded to $g \cdot b_l$. The adversary could choose to allocate each overlay path to a different Sybil identity, resulting in $g \cdot b_l$ Sybil identities in the DHT (in the routing tables of honest nodes). We can further limit the number of Sybil identities in the routing tables of honest nodes by ensuring that the adversary must allocate at least a threshold t number of overlay paths per Sybil identity. This would bound the number of Sybil identities in honest nodes routing tables to $g \cdot b_l/t$. Note that the number of overlay paths between the honest and Sybil regions does not change. We propose the following mechanism to ensure that the adversary sets up trails with at least a threshold t overlay neighbors. Nodes periodically probe their overlay neighbors to check if each successor in their routing table has set up a trail with at least t other nodes in the overlay neighborhood. Note that the check is performed by directly querying the overlay neighbors. The threshold t is set to $t < 2 \cdot \mathit{num\_successors}$ to account for malicious overlay nodes returning incorrect replies. If the adversary does not allocate t trails per Sybil identity (set up with its successors and predecessors), the honest nodes can detect this via probing and can teardown the trails to the malicious Sybil identity. Note that the adversary cannot game the probing mechanism unless it has a large number of Sybil identities in the overlay neighborhood of a node. Since the Sybil identities are distributed at random in the overlay namespace, this is unlikely to happen unless the adversary has a large number of attack edges ($g \in \Omega(n/(\log n))$).

Securing routing table maintenance: We provide the following defenses to attacks on routing table maintenance:

Trail interception attacks: Observe that our mechanism to defend against Sybil attacks, i.e., bounding the number of trails that traverse a social network link, also defends against malicious nodes that attempt to be a part of a large number of trails. Specifically, the adversary has a *quota* of $g \cdot b_l$ trails between honest nodes and itself, and it can choose to utilize this quota either by inserting Sybil identities in the DHT or by being part of trails between two honest nodes. Either way, the effect of this attack is limited by the bound b_l.

Trail construction attacks: Suppose that a node X is trying to set up a trail with its overlay neighbor Y. To circumvent the scenario where a malicious intermediate node M simply drops X's path set up request to Y, we propose that upon path setup the end point Y sends an acknowledgment along the reverse path back to X. If after a timeout, the node X does not receive an acknowledgment from Y, then it can retry sending the trail set up request over a different route. Again, the fast-mixing nature of the social network topology guarantees that two nodes are very likely to have multiple paths between each other.

Message integrity and forgery attacks: To provide message integrity is the use of self-certifying identifiers [8, 15, 38]. Nodes can append their public keys to the message and produce a digital signature of the message along with the appended public key. The self-certifying nature of identifiers ensures that the public key for a specified node identifier cannot be forged; this enables us to provide both message integrity as well as authentication.

Securing the lookup protocol: Even if the routing table maintenance protocol is secure, the adversary can still drop or misroute lookup requests that traverse itself. We secure the lookup protocol using redundant routing, similar to Castro et al. [16]. Instead of a single lookup, a node can choose to perform r lookups for the destination (where r is the redundancy parameter) using r diverse trusted links in the social network topology. Redundant routing increases the probability that at least one lookup will traverse only honest nodes and find the correct successor. If the lookup is performed during route table maintenance, the correct successor can be identified since it will be impossible to set up a trail to an incorrect one; if the lookup is searching for a particular node or data item, then self-certifying techniques can be used to identify incorrect responses.

4.3 Privacy Protection

All communication in X-Vine happens over social network links; while a user's IP address is revealed to his/her social contacts, it is not exposed to random peers in the network. Therefore as long as a user's social contacts are trusted, he/she can communicate pseudonymously. Moreover, observe that X-Vine's mechanisms do not require a user to expose his/her social contacts. This is in sharp contrast to prior work [34], wherein this information is revealed as part of protocol operations to everyone in the network. Note that in the absence of a mapping from a DHT ID to an IP address, the adversary cannot perform traffic analysis to infer social contacts. The only source of information leakage is when the adversary can map DHT IDs of two users to their respective IP addresses (for example, by virtue of being their trusted contacts); in this case the adversary can perform traffic analysis attacks to infer whether the two users have a trust relationship or not. In X-Vine, the privacy risk is with respect to social contacts, rather than random peers in the network. Note that in this paper, we are only concerned with overlay level adversaries; adversaries which operate at the ISP level, or have external sources of information [47] are outside the scope of our threat model.

5 Experiments and Analysis

We evaluate X-Vine with theoretical analysis, experiments using real-world social network topologies, and a prototype implementation. We measure routing state size, lookup path lengths, security against Sybil attacks, resilience against churn, and lookup latency. We also developed a Facebook application to facilitate the use of our design.

Simulation environment: We constructed an in-house event-driven simulator. As done in [14], we bootstrap X-Vine by selecting a random node in the social network as the first node, and the social network neighbors of that node then become candidates to join the X-Vine network. Next, one of these neighbors is selected to join, with a probability proportional to the number of trust relationships it has with nodes that are already a part of the X-Vine network. This process is then repeated. Note that some nodes may not be successful in joining because of the bound on number of trails per link (as discussed in detail later).

Data sets: Recent work has proposed the use of interaction graphs [62, 66] as a better indicator of real world trust than friendship graphs. Hence we consider both traditional social network graph topologies as well as interaction graph topologies in our evaluation. The datasets that we use have been summarized in Table 1.

Facebook friendship graph from the New Orleans regional network [62]: The original dataset consists of 60 290 nodes and 772 843 edges. We processed the dataset in a manner similar to the evaluation done in SybilLimit [68] and SybilInfer [21], by imposing a lower bound of 3 and an upper bound of 100 on the node degree (see [21, 68] for details) [2]. After processing, we are left with 50 150 nodes and 661 850 edges.

Facebook wall post interaction graph from the New Orleans regional network [62]: The original dataset consists of 60 290 users. After processing, we are left with 29 140 users and 161 969 edges. Note that links in this dataset are directed, and we consider an edge between users only if there were interactions in both directions.

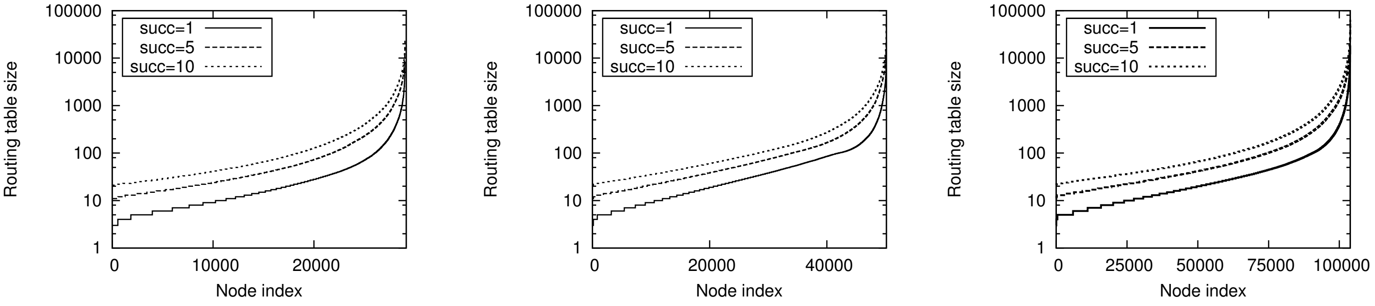
Facebook interaction graph from a moderate-sized regional [3] network [66]: The dataset consists of millions of nodes and edges, but our experiments are memory limited and do not scale to millions of nodes. Instead, we first truncate the dataset by considering only a four hop neighborhood from a seed node. After processing, we are left with 103 840 nodes and 961 418 edges.

Synthetic scale-free graphs: Social networks exhibit a scale-free node degree topology [53]. Our network synthesis algorithm replicates this structure through preferential attachment, following the methodology of Nagaraja [45]. The use of synthetic scale free topologies enables us evaluate X-Vine while varying the number of nodes in the network.

Overhead: Figure 4 plots the routing table size for different successor list sizes. We can see the temporal correlation effect here, as the distribution of state shows super-exponential growth. Temporal correlation is highly unde-

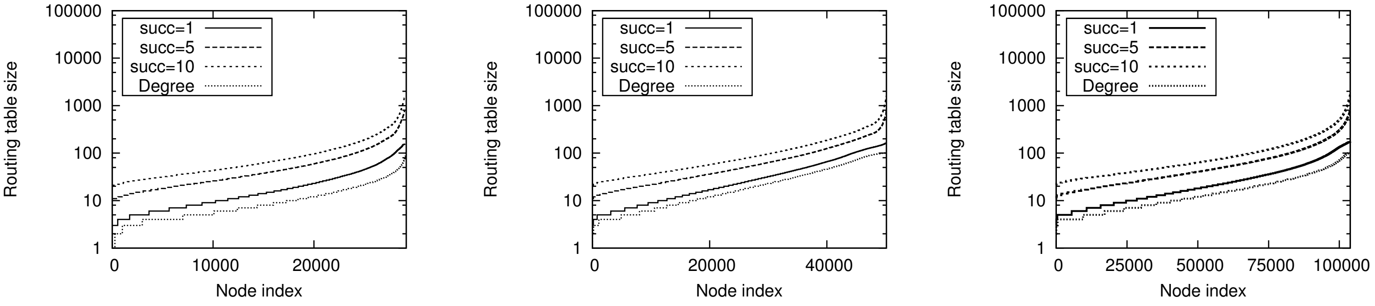
[2] Recent work by Mohaisen et al. [44] shows that social networks may not be as fast mixing as previously believed. However, we note that their results do not directly apply to X-Vine since they did not consider node degree bounds in their analysis. X-Vine excludes users having few friends from participating in the routing protocol, though such users could use their trusted friends to lookup keys.

[3] Because of privacy reasons, the name of the regional network has been left anonymous by the authors of [66].



(a) (b) (c)

Figure 4. *Routing state, with no bounds on state:* **(a) New Orleans Interaction graph, (b) New Orleans Friendship graph, and the (c) Anonymous Interaction graph. Due to temporal correlation, some nodes exhibit high state requirements.**



(a) (b) (c)

Figure 5. *Routing state, with node and edge bounds:* **(a) New Orleans Interaction graph, (b) New Orleans Friendship graph, and (c) Anonymous Interaction graph. Bounding state significantly reduces state requirements. Using a successor list of size 5, the average routing state for the three topologies is 67, 81, and 76 records respectively. X-Vine requires orders of magnitude less state than Whanau [34].**

Table 1. Topologies

Dataset	Nodes	Edges	Mean Degree
New Orleans Facebook Friendship graph	50 150	661 850	26.39
New Orleans Facebook Interaction graph	29 140	161 969	11.11
Anonymous Facebook Interaction graph	103 840	961 418	18.51

sirable both from a performance and a security standpoint. If the few nodes with very large state become unavailable due to churn, the network could get destabilized. Moreover, if one of these nodes is malicious, it could easily intercept a large number of lookups and drop them. To address this, we enable the routing policy that bounds the number of paths traversing nodes and links. Based on our analytic model in Appendix A, we propose the following bound on the number of paths per link: $b_l = \alpha \cdot 2 \cdot num\_successors \cdot \log(n)$, where α is a small fixed constant. The bound per link ensures that if a node has degree d, then its routing table size will never exceed $d \cdot b_l \in O(\log n)$. We can see that the routing state does not undergo an exponential increase as in previous plots. Moreover, routing state increases with node degrees, which is desirable. Based on these routing table sizes, we can estimate the communication overhead of X-Vine by computing the cost of sending heartbeat traffic for all records in the routing table. Considering the routing table size to be 125 records, UDP ping size to be 40 bytes, and a heartbeat interval of 1 s, the estimated mean communication overhead is only 4.8 KBps.

Comparison with Whanau [34]: Routing state in Whanau depends on the number of objects stored in the DHT. Routing tables in Whanau are of size $\Theta(\sqrt{n_o} \log n_o)$, where n_o is the number of objects in the DHT. If there are too many objects stored in the DHT, Whanau resorts to maintaining information about all the nodes and edges in the social network (increasing state/overhead to $\Theta(n)$). If there are too few objects in the DHT, Whanau resorts to flooding to find objects [34]. We note that such properties make Whanau unsuitable for many common applications. Even if we consider the case where each node in the DHT stores only tens of objects, the average routing table size in Whanau for the $103\,840$ node anonymous interaction graph is about $20\,000$ records—an increase of more than two orders of magnitude as compared with X-Vine. If we consider a heartbeat interval of 1 second in Whanau (in order to accurately maintain object states for common DHT applications), the resulting communication overhead is about 800 KBps. This difference increases further with an increase in the number of objects in the DHT or the size of the network. For instance, we scaled up our experiments to a larger $613\,164$ node anonymous interaction graph topology using a machine with 128 GB RAM, and found that the average routing state in X-Vine using a successor list size of 10 was only 195 records, as compared with more than $50\,000$ records in Whanau. (Note that routing state in X-Vine is independent of the number of objects in the DHT.)

False Positive Analysis: Next, we consider the impact of link/node path bounds on honest node's ability to join the DHT. We found that most honest nodes were able to join the DHT due to the fast mixing nature of honest social networks. In fact, for all our experimental scenarios, the false-positive rate was less than 0.5%, which is comparable to the state-of-the-art systems [21,68]. By tuning the parameter b_l, it is possible to trade off the false-positive rate for Sybil resilience: b_l will reduce the false-positive rate at the cost of increasing the number of Sybil identities in the system. For the remainder of the paper, we shall use $\alpha = 1, \beta = 5$.

Path Length Analysis: Table 2 depicts the mean lookup path lengths for the real world datasets with varying successor list sizes and varying redundancy parameter. We first observe that lookup performance improves with increasing successor list sizes. For example, in the New Orleans interaction graph, the mean lookup path length decreases from 97.9 to 15.4 when the successor list size increases from 1 to 20 (using $r = 1$). Further improvements in performance can be realized by performing redundant lookups as described in Section 4 and caching the lookup with the smallest path length. We can see that in the same dataset, mean lookup path length decreases from 15.4 to 10.3 when the redundancy parameter is increased from $r = 1$ to $r = 5$ (using successor list of size 20). Further increases in redundancy show diminishing returns. Observe that when the successor list size is at least 10, and the redundancy parameter is at least 10, then the mean lookup path lengths for all datasets are less than 15 hops. Increasing the successor list size to 20 (and keeping $r = 10$) reduces this value to less than 11.5 for all datasets.

Security under Sybil Attack: Recall that if the adversary has g attack edges, then the number of trails between the honest and the Sybil subgraph is bounded by $g \cdot b_l$ (regardless of the attacker strategy). Our attack methodology is as follows: we randomly select a set of compromised nodes until the adversary has the desired number of attack edges. The compromised nodes then launch a Sybil attack, and set up trails between Sybil identities and their overlay neighbors. If the trail set up request starting from a Sybil node gets shortcutted back to the Sybil identities, the request is backtracked. This ensures that the adversary uses only a single attack edge per trail. Node identifiers of Sybil identities are chosen at random with the adversarial goal of intercepting as many lookups as possible. All lookups traversing compromised/Sybil nodes are considered unsuccessful.

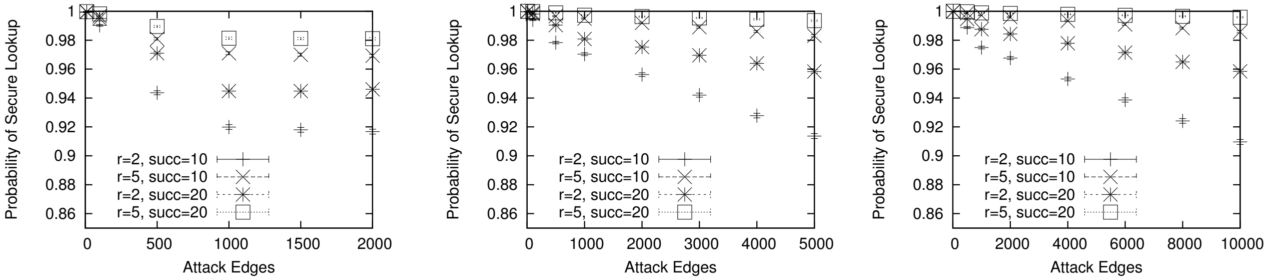
Figure 6 plots the probability of a secure lookup as a function of number of attack edges, redundancy parameter, and size of successor list. We find that the probability of secure lookup increases as the redundancy parameter is increased. This is because as the number of redundant lookups increases, there is a greater chance that a lookup will traverse only honest nodes and return the correct result. We also find that the probability of secure lookup also increases when the size of the successor list increases. This is because increasing successor list size reduces the mean lookup path length, reducing the probability that an adversary can intercept the lookup query. As long as $g \in o(n/(\log n))$, the probability of secure lookup can be made arbitrarily high by increasing the redundancy parameter and the successor list size. Finally, reducing b_l would further limit the impact of Sybil identities, at the cost of increased false positives.

Churn Analysis: Next, we evaluate the performance of X-Vine under churn. We are interested in the *static resilience* of X-Vine, i.e., the probability of lookup success after a fraction of the nodes in the system fail simultaneously. To account for churn, we modified the lookup algorithm to *backtrack* whenever it cannot make forward progress in the overlay namespace. Figure 7 depicts the mean probability of lookup success as a function of the fraction of nodes that fail simultaneously, averaged over $100\,000$ lookups. Similar to the analysis of lookup security, we can see that an increase in either the redundancy parameter or the successor list size result in improved resilience against churn. We can also see that as the fraction of failed nodes increases, the probability of lookup success decreases, but is still greater than 0.95 for all scenarios using $r = 4$ and $succ = 20$.

PlanetLab Implementation: To validate our design and evaluate lookup latency in real-world environments, we implemented the X-Vine lookup protocol in C++ as a single-threaded program using $3\,000$ LOC. We used libasync [5, 6] and Tame [32] to implement non-blocking socket func-

Table 2. Mean Lookup Path Length

# Succ	New Orleans interaction graph			New Orleans friendship graph			Anonymous interaction graph		
	$r = 1$	$r = 5$	$r = 10$	$r = 1$	$r = 5$	$r = 10$	$r = 1$	$r = 5$	$r = 10$
1	97.9	57.7	51.7	103.6	57.5	48.1	166.7	96.3	81.0
5	30.0	18.2	16.8	34.8	19.3	16.7	48.9	25.5	21.7
10	20.2	13.0	12.16	23.1	13.7	12.1	29.9	16.9	14.8
20	15.4	10.3	9.6	17.0	10.7	9.45	21.0	12.8	11.3



(a) (b) (c)

Figure 6. Probability of secure lookup as a function of number of attack edges for (a) New Orleans interaction graph, (b) New Orleans friendship graph, and (c) Anonymous Interaction graph.

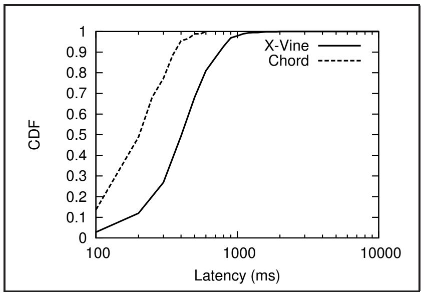


Figure 8. Lookup latency

tionality (UDP) in an event-based fashion. We ran our implementation over 100 randomly selected nodes in the PlanetLab network. We used a synthetic scale free graph as the social network topology. The duration of the experiment was set to 1 hour, and nodes performed lookups every 1 second. Figure 8 depicts the CDF of observed one-way lookup latencies. We can see that the median lookup latency was only 400 ms (as compared to 200 ms in Chord), for the mean lookup path length of 5 hops (not shown in the Figure). Using these values, we can estimate the median lookup latency for mean lookup path lengths of 10 hops and 15 hops (that were observed in our experiments over real world social network topologies in Table 2) to be about 800 ms and 1200 ms respectively. We see some outliers in Figure 8 due to the presence of a few slow/unresponsive nodes in PlanetLab. For this experiment, we mapped vertices in the social network topology to random PlanetLab nodes (possibly in different geographic locations). Thus, our analysis is conservative; accounting for locality of social network contacts would likely improve the lookup performance.

Facebook Application: To bootstrap a X-Vine node, its user needs to input the IP addresses of his/her friends. Since this can be a cumbersome for a user, we implemented a Facebook application (available at `http://apps.facebook.com/x--vine`) that automates this process and improves the usability of our design. The work flow of the application is as follows: (i) When a user visits the Facebook application URL, Facebook checks the credentials of the user, the user authorizes the application, and then the request gets redirected to the application hosting server. (ii) The application server authenticates itself, and is then able to query Facebook for user information. The application server records the user information along with the user IP address. (iii) The application server then queries Facebook for a list of user's friends, and returns their previously recorded IP addresses (if available) to the user.

This list of IP addresses could then be used by the DHT software to bootstrap its operations. Our implementation demonstrates that a user's social contacts can be integrated into the DHT protocol using only a few hundred lines of glue code. Keeping in spirit with our fully decentralized design goal, in future, our application could be implemented on a decentralized platform like Diaspora [1] such that the app server is not a central point of trust or failure.

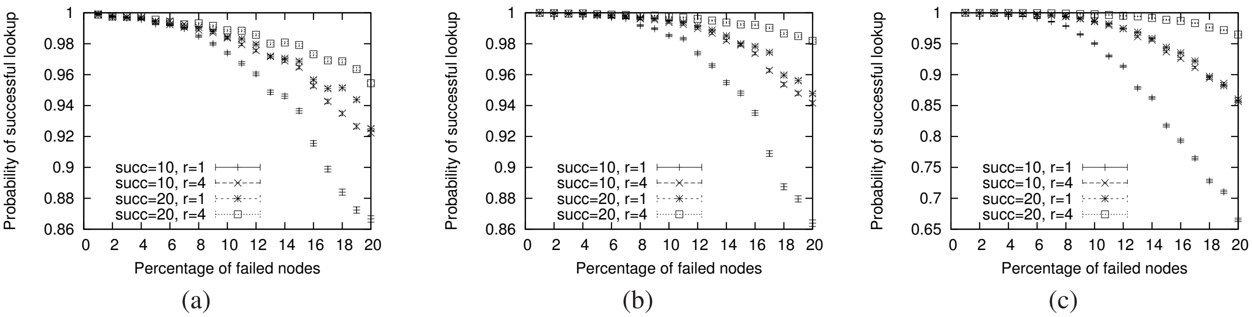


Figure 7. *Lookup resilience against churn:* **(a) New Orleans Interaction graph, (b) New Orleans Friendship graph, and (c) Anonymous Interaction graph.**

6 Related Work

X-Vine provides *multi-hop* social network routing, logarithmic state Sybil defense, protects privacy of friendship information, and enables pseudonymous communication. Our work is the first to provide these properties. However, X-Vine builds upon foundational work in several areas:

Sybil defense: Sybil defenses must fundamentally impose a cost on participation in the network [22]. One approach, advocated by Castro et al. [16], requires users to provide identity credentials and/or payment to a centralized authority, who then issues certificates allowing users to participate. This authority, of course, becomes a central point of trust. Decentralized approaches instead allow nodes to directly verify some resource expenditure by other nodes, such as CPU computation, or the possession of a unique IP address [12,55]. All these solutions face a tradeoff between creating too high a barrier for participation by honest users and making it too easy for malicious users to create Sybil identities. More recent work has recognized that it is expensive for a malicious adversary to establish trust relationships with honest users and thus social network topologies can be used to detect and mitigate social Sybil attacks. The design of X-Vine is based upon the same principle.

SybilGuard [69] and SybilLimit [68] are decentralized systems for Sybil defense. These systems use special random walks called *random routes* for Sybil defense. In SybilLimit, as long as the number of attack edges is less than a threshold ($g = o\left(\frac{n}{\log n}\right)$), then with high probability, a short random walk of $O(\log n)$ steps is likely to stay within the set of honest nodes. Nodes in SybilLimit perform $\sqrt{e}$ short random walks (where e is the number of edges amongst the honest nodes) and keep track of their last edges (tails). By the birthday paradox, two honest nodes will share a common tail with high probability. Each node allows only a certain number of random routes to traverse it, thereby limiting the number of Sybil identities that are validated by the honest nodes.

SybilInfer [21] provides an algorithm for labeling nodes in a social network as honest users or Sybils controlled by an adversary. It takes as an input a social graph G, and generates a set of traces using short random walks. Using a mathematical model of an honest social network, it performs Bayesian inference to output a set of dishonest nodes. The Bayesian inference approach can even be used to assign probabilities to nodes of being honest or dishonest. These systems are standalone Sybil defenses and do not provide a DHT functionality.

Whanau [34] is the state of art Sybil resilient DHT [20, 33] where nodes can communicate with only one intermediate hop. Each node performs $\sqrt{e}$ random walks to sample nodes for construction of their routing tables ; the Sybil resistant property of short random walks ensures that a high fraction of the sampled nodes are honest . By querying routing table entries, nodes can construct their successor lists. As compared to X-Vine, Whanau provides its properties at the cost of maintaining $\sqrt{n_o} \log n_o$ state at each node (where n_o is the number of objects). The large state requirements mean that the system has difficulty maintaining accurate state in face of object churn. Whanau also requires the entire social graph to be public, presenting significant privacy concerns. In contrast, X-Vine builds upon *network-layer* DHTs, embedding the DHT directly into the social network fabric. This enables X-Vine to provide good security while achieving improved scalability and privacy of social relationships. Moreover, X-Vine provides support for pseudonymous communication.

The concept of a bottleneck cut between a fast-mixing social network and Sybil nodes has been used in a number of other systems, such as SumUp [60], a protocol for online content rating that is resilient to Sybil attacks; Ostra [41], a system to prevent unwanted communication from nodes; and Kaleidoscope [58], a system for censorship resistance.

Security and privacy in DHTs: Other work deals with the issue of secure routing when a fraction of nodes in the DHT are compromised [16,31,46,57,63]. Sit and Morris [57], as well as Wallach [63] discuss security issues in DHTs. Castro [16] proposed the use of redundant routing to improve the lookup security. Nambiar and Wright [46] showed that redundant lookups in Chord may traverse a few common nodes, and thus a few malicious nodes could subvert all of the redundant lookups. They designed the Salsa DHT in which redundant lookups are unlikely to traverse common nodes. Kapadia and Triandopoulos [31] propose to make redundant routes diverse by making use of the observation that to perform a lookup for A, it suffices to lookup the nodes which have A as its finger, and then query them. Unlike X-Vine these systems are not concerned with the problem of Sybil attacks. Another line of research deals with the privacy of the DHT lookup. Borisov [11] as well as Ciaccio [18] proposed to incorporate anonymity into the lookup, but their algorithms do not consider active attacks. More recently, anonymous and secure lookups were considered in the designs of Salsa [46], NISAN [48], and Torsk [39]. However, recent work [42, 65] showed vulnerabilities in all the three designs. X-Vine improves the privacy of a user by enabling pseudonymous communication; the IP address of a user is revealed only to a user's trusted friends.

Social networks and routing: The benefits of using social network links for overlay routing has been recognized in a large body of academic work as well as deployed systems.

Hybrid routing using social network links: Systems in this class maintain traditional peer-to-peer structures but also make use of social network connections. Sprout [36] proposed augmenting the finger tables in traditional DHTs, such as Chord, with social network links. The authors showed that the added connections could improve the security of the routing mechanism. However, Sprout does not defend against Sybil attacks, and is not concerned with user privacy. OneSwarm [30] is a deployed peer-to-peer communication system for improving user privacy where routing is performed by combining trusted and untrusted peer relationships. Tribler [51] increases download speed in BitTorrent by discovering and downloading file chunks stored at peers. Similarly, Maze [17] leverages a social network to discover peers and cooperatively download files. These three systems leverage flooding to provide any-to-any reachability, and thus cannot scale to large networks. The hybrid systems are not resilient to Sybil attacks. Moreover, they allow direct contacts over untrusted links, exposing users' IP addresses.

Routing only using social network links: All communication in this class of systems is over social network links. This enables participants in the network to be hidden from each other, providing a high degree of privacy. Such a network is commonly known as a *darknet*. WASTE [24] is a deployed decentralized chat, instant messaging, and file sharing protocol, and is widely considered to be the first darknet. WASTE does not attempt to scale beyond small networks, and its suggested size is limited to 50 users. Turtle [50] is a deployed decentralized anonymous peer-to-peer communication protocol. Nodes in Turtle do not maintain any state information other than their trusted friend links and use controlled flooding to search for data items. Flooding methods create significant overhead as network size increases. Freenet [19] is a deployed decentralized censorship-resistant distributed storage system. Version 0.7 of Freenet nodes can be configured to run in darknet or opennet mode; the latter allows connections from untrusted nodes, and is expected to be used by less privacy-sensitive users. Freenet's routing algorithm is heuristic and does not guarantee that data will be found at all; it has also been shown to be extremely vulnerable even against a few malicious nodes [23]. Membership concealing overlay networks (MCONs) (formalized by Vasserman et al. [61]), hide the real-world identities of the participants through the use of overlay and DHT-based routing. However, their design makes use of a trusted centralized server and also requires flooding when a new user joins the network. In addition to these limitations, none of the above systems are resilient to Sybil attacks.

7 Limitations

We now discuss some limitations of our design. First, X-Vine requires a user's social contacts to be part of the overlay; the DHT needs to be bootstrapped from a single contiguous trust network. Next, X-Vine assumes that Sybil identities are distributed randomly in the DHT identifier space. We emphasize that this assumption is shared by prior systems [20], and that defending multi-hop DHTs against targeted clustering attacks is currently an open problem. In future work, we will investigate the possibility of adapting the cuckoo hashing mechanism [33] proposed by Lesniewski-Laas (for one-hop DHTs) in the context of securing multi-hop DHTs. X-Vine also does not defend against attackers who target users by compromising nodes close to them in the social network topology. Finally, applications using X-Vine experience higher than usual latencies since all communications are pseudonymous and traverse multiple social network links.

8 Conclusions

We describe X-Vine, a protection mechanism for DHTs that operates entirely by communicating over social network links. X-Vine requires $O(\log n)$ state, two orders of magnitude less in practical settings as compared with existing techniques, making it particularly suitable for large-scale and dynamic environments. X-Vine also enhances privacy by not revealing social relationship information and by providing a basis for pseudonymous communication.

References

[1] Diaspora. wwww.joindiaspora.com/.

[2] eMule. http://www.emule-project.net/.

[3] Facebook. www.facebook.com.

[4] Livejournal. www.livejournal.com.

[5] Sfslite. http://www.okws.org/doku.php?id=sfslite.

[6] Using libasync. http://pdos.csail.mit.edu/6.824-2004/async/.

[7] The Vuze Network. http://www.vuze.com/.

[8] D. G. Andersen, H. Balakrishnan, N. Feamster, T. Koponen, D. Moon, and S. Shenker. Accountable Internet protocol. In *SIGCOMM*, 2008.

[9] K. Bauer, D. Mccoy, D. Grunwald, and D. Sicker. Bitstalker: Accurately and efficiently monitoring bittorent traffic. In *Proceedings of the International Workshop on Information Forensics and Security*, 2009.

[10] L. Bilge, T. Strufe, D. Balzarotti, and E. Kirda. All your contacts are belong to us: automated identity theft attacks on social networks. In *WWW*, 2009.

[11] N. Borisov. *Anonymous routing in structured peer-to-peer overlays*. PhD thesis, UC Berkeley, 2005.

[12] N. Borisov. Computational puzzles as sybil defenses. In *IEEE P2P*, 2006.

[13] Y. Boshmaf, I. Muslukhov, K. Beznosov, and M. Ripeanu. The socialbot network: when bots socialize for fame and money. In *ACSAC*, 2011.

[14] M. Caesar, M. Castro, E. Nightingale, A. Rowstron, and G. O'Shea. Virtual Ring Routing: Network routing inspired by DHTs. In *SIGCOMM*, 2006.

[15] M. Caesar, T. Condie, J. Kannan, K. Lakshminarayanan, and I. Stoica. ROFL: Routing on Flat Labels. In *SIGCOMM*, September 2006.

[16] M. Castro, P. Druschel, A. Ganesh, A. Rowstron, and D. S. Wallach. Secure routing for structured peer-to-peer overlay networks. In *OSDI*, 2002.

[17] H. Chen, X. Li, and J. Han. Maze: a social peer-to-peer network. In *In of CEC-East*, 2004.

[18] G. Ciaccio. Improving sender anonymity in a structured overlay with imprecise routing. In *PETS*, June 2006.

[19] I. Clarke, O. Sandberg, B. Wiley, and T. W. Hong. Freenet: A distributed anonymous information storage and retrieval system. In *DPET*, July 2000.

[20] G. Danezis, C. Lesniewski-Laas, M. F. Kaashoek, and R. Anderson. Sybil-resistant DHT routing. In *ESORICS*, Milan, Italy, September 2005.

[21] G. Danezis and P. Mittal. SybilInfer: Detecting sybil nodes using social networks. In *NDSS*, 2009.

[22] J. Douceur. The Sybil Attack. In *IPTPS*, March 2002.

[23] N. S. Evans, C. GauthierDickey, and C. Grothoff. Routing in the dark: Pitch black. *ACSAC*, 2007.

[24] J. Frankel. http://waste.sourceforge.net.

[25] M. J. Freedman, E. Freudenthal, and D. Mazières. Democratizing content publication with Coral. In *NSDI*, 2004.

[26] M. J. Freedman and R. Morris. Tarzan: a peer-to-peer anonymizing network layer. In *CCS*, 2002.

[27] R. Geambasu, T. Kohno, A. A. Levy, and H. M. Levy. Vanish: increasing data privacy with self-destructing data. In *USENIX Security*, 2009.

[28] E. Gilbert and K. Karahalios. Predicting tie strength with social media. In *Computer Human Interaction*, 2009.

[29] D. Irani, M. Balduzzi, D. Balzarotti, E. Kirda, and C. Pu. Reverse social engineering attacks in online social networks. In *DIMVA*, 2011.

[30] T. Isdal, M. Piatek, A. Krishnamurthy, and T. Anderson. Privacy-preserving p2p data sharing with oneswarm. In *SIGCOMM*, 2010.

[31] A. Kapadia and N. Triandopoulos. Halo: High-assurance locate for distributed hash tables. In *NDSS*, 2008.

[32] M. Krohn, E. Kohler, and M. F. Kaashoek. Events can make sense. In *USENIX ATC*, 2007.

[33] C. Lesniewski-Laas. A Sybil-proof one-hop DHT. In *SocialNets*, pages 19–24, 2008.

[34] C. Lesniewski-Laas and M. F. Kaashoek. Whanaungatanga: A Sybil-proof distributed hash table. In *NSDI*, 2010.

[35] M. Liberatore, B. N. Levine, and C. Shields. Strengthening forensic investigations of child pornography on p2p networks. In *CONEXT*, 2010.

[36] S. Marti, P. Ganesan, and H. Garcia-Molina. SPROUT: P2P routing with social networks. In *P2P&DB*, 2004.

[37] P. Maymounkov and D. Mazières. Kademlia: A peer-to-peer information system based on the xor metric. In *IPTPS*, 2002.

[38] D. Mazieres. *Self-certifying file system*. PhD thesis, MIT, 2000. Supervisor-Kaashoek, M. Frans.

[39] J. McLachlan, A. Tran, N. Hopper, and Y. Kim. Scalable onion routing with Torsk. In *CCS*, 2009.

[40] E. Miluzzo, N. D. Lane, K. Fodor, R. Peterson, H. Lu, M. Musolesi, S. B. Eisenman, X. Zheng, and A. T. Campbell. Sensing meets mobile social networks: the design, implementation and evaluation of the cenceme application. In *SenSys*, 2008.

[41] A. Mislove, A. Post, P. Druschel, and K. P. Gummadi. Ostra: leveraging trust to thwart unwanted communication. In *NSDI*, pages 15–30, 2008.

[42] P. Mittal and N. Borisov. Information leaks in structured peer-to-peer anonymous communication systems. In *CCS*, 2008.

[43] P. Mittal and N. Borisov. Shadowwalker: peer-to-peer anonymous communication using redundant structured topologies. In *CCS*, 2009.

[44] A. Mohaisen, A. Yun, and Y. Kim. Measuring the mixing time of social graphs. In *IMC*, 2010.

[45] S. Nagaraja. Anonymity in the wild: Mixes on unstructured networks. In *PET*, pages 254–271, 2007.

[46] A. Nambiar and M. Wright. Salsa: a structured approach to large-scale anonymity. In *CCS*, pages 17–26, New York, NY, USA, 2006. ACM.

[47] A. Narayanan and V. Shmatikov. De-anonymizing social networks. In *IEEE S & P*, 2009.

[48] A. Panchenko, S. Richter, and A. Rache. NISAN: network information service for anonymization networks. In *CCS*, 2009.

[49] C. Perkins, E. Belding-Royer, and S. Das. Ad hoc on-demand distance vector (AODV) routing, 2003.

[50] B. Popescu, B. Crispo, and A. S. Tanenbaum. Safe and private data sharing with Turtle: Friends team-up and beat the system. In *12'th Cambridge International Workshop on Security Protocols*, April 2004.

[51] J. Pouwelse, P. Garbacki, J. Wang, A. Bakker, J. Yang, A. Iosup, D. Epema, M. Reinders, M. van Steen, and H. Sips. Tribler: A social-based peer-to-peer system. Technical report, Delft University of Technology, Feb 2006.

[52] S. Ratnasamy, P. Francis, M. Handley, and R. Karp. A scalable content-addressable network. In *SIGCOMM*, August 2001.

[53] M. Ripeanu, A. Iamnitchi, and I. Foster. Mapping the Gnutella network. *IEEE Internet Computing*, 2002.

[54] T. Ristenpart, G. Maganis, A. Krishnamurthy, and T. Kohno. Privacy-preserving location tracking of lost or stolen devices: cryptographic techniques and replacing trusted third parties with DHTs. In *USENIX Security*, 2008.

[55] H. Rowaihy, W. Enck, P. McDaniel, and T. L. Porta. Limiting sybil attacks in structured p2p networks. In *INFOCOM*, 2007.

[56] A. Rowstron and P. Druschel. Pastry: scalable, decentralized object location and routing for large-scale peer-to-peer systems. In *ACM Middleware*, November 2001.

[57] E. Sit and R. Morris. Security considerations for peer-to-peer distributed hash tables. In *IPTPS*, 2002.

[58] Y. Sovran, J. Li, and L. Subramanian. Unblocking the internet: Social networks foil censors. Technical report, NYU, 2008.

[59] I. Stoica, R. Morris, D. Karger, M. Kaashoek, and H. Balakrishnan. Chord: a scalable peer-to-peer lookup service for Internet applications. In *SIGCOMM*, 2001.

[60] N. Tran, B. Min, J. Li, and L. Subramanian. Sybil-resilient online content voting. In *NSDI*, pages 15–28, 2009.

[61] E. Vasserman, R. Jansen, J. Tyra, N. Hopper, and Y. Kim. Membership-concealing overlay networks. In *CCS*, pages 390–399, 2009.

[62] B. Viswanath, A. Mislove, M. Cha, and K. P. Gummadi. On the evolution of user interaction in Facebook. In *WOSN*, 2009.

[63] D. Wallach. A survey of peer-to-peer security issues. In *International Symposium on Software Security*, Tokyo, Japan, 2002.

[64] P. Wang, J. Tyra, E. Chan-Tin, T. Malchow, D. F. Kune, N. Hopper, and Y. Kim. Attacking the Kad network. In *SecureComm*, 2008.

[65] Q. Wang, P. Mittal, and N. Borisov. In search of an anonymous and secure lookup: attacks on structured peer-to-peer anonymous communication systems. In *CCS*, 2010.

[66] C. Wilson, B. Boe, A. Sala, K. P. Puttaswamy, and B. Y. Zhao. User interactions in social networks and their implications. In *EuroSys*, pages 205–218, 2009.

[67] S. Wolchok, O. S. Hofmann, N. Heninger, E. W. Felten, J. A. Halderman, C. J. Rossbach, B. Waters, and E. Witchel. Defeating vanish with low-cost sybil attacks against large DHTs. In *NDSS*, 2010.

[68] H. Yu, P. Gibbons, M. Kaminsky, and F. Xiao. SybilLimit: A near-optimal social network defense against sybil attacks. In *IEEE Security and Privacy*, 2008.

[69] H. Yu, M. Kaminsky, P. Gibbons, and A. Flaxman. SybilGuard: Defending against Sybil attacks via social networks. In *SIGCOMM*, 2006.

A Mathematical Analysis of X-Vine:

As a first step in formally modeling X-Vine security, we develop an analytic model for routing in X-Vine. The model enhances our understanding of the relationship between operational parameters of X-Vine, and can serve as a stepping stone for a complete formal model to analyze X-Vine's security against Sybil identities.

Let there be N nodes in the system with node identifiers ranging from $0..N-1$. Let $L(0,w)$ be the expected lookup path length between the node with identifier 0 and w. Let us suppose that node maintain trails with a single successor. Without loss of generality, the average lookup path length can be computed as follows:

$$E(L) = \frac{\sum_{w=0}^{w=N-1} L(0,w)}{N} \tag{1}$$

In the simplest case, $L(0,0) = 0$. Let us first compute $L(0,1)$. Note that node 0 and node 1 have a *trail* between them because they are overlay neighbors. Let d be the average node degree in the underlying topology. We assume that the length of the trail between overlay neighbors is close to their shortest path in the social network topology (approximately $\log_d(N)$). The lookup will proceed from node 0 along the trail to node 1. Thus we have that:

$$L(0,1) = \text{Expected trail length} \tag{2a}$$

$$L(0,1) = \log_d(N) \tag{2b}$$

Notice that there cannot be any shortcutting in the intermediate nodes on the trail path from node 0 to node 1 because we have assumed the trail to be the shortest path in the social network topology. Let us now compute $L(0,2)$. There are two possible scenarios. In the first case, there may be a trail with an end point at node 2 *going through* node 0. In this case, the packet is routed along the trail to node 2. Again, there cannot be any shortcutting along this trail because it is the shortest path. The mean path length in this case is $\frac{\log_d N}{2}$. In the second case, the packet will be routed towards overlay node 1 (successor of node 0). Thus we have that:

$$\begin{aligned} L(0,2) = {} & P(\text{trail}) \cdot \frac{\log_d N}{2} \\ & + (1 - P(\text{trail})) \cdot (1 + l((\log_d N) - 1, 1, 2)) \end{aligned} \tag{3a}$$

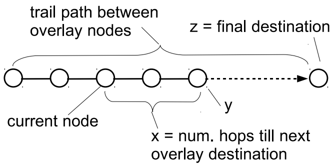

trail path between overlay nodes
z = final destination
y
current node
x = num. hops till next overlay destination

Figure 9. X-Vine lookup

where $l(x, y, z)$ is defined as the expected path length when z is the destination identifier, y is the next overlay hop in the lookup, and x is the physical distance along a trail between the current node and y (Figure 9). This means that $l((\log_d N) - 1, 1, 2)$ is the expected path length when the destination identifier is 2, the next overlay hop is 1, and the next overlay hop is $\log_d N$ hops away from the current node.

Note that each node maintains a trail to its successor, and the mean length of the trails is $\log_d(N)$. This means that the average routing state maintained by a node in the system is $\log_d(N)$. Since each routing table entry specifies two end points for a trail, the probability that a node has a trail with a particular end point going through it is $\frac{2\log_d N}{N}$. Thus:

$$L(0,2) = \frac{2\log_d N}{N} \cdot \frac{\log_d N}{2} + \left(1 - \frac{2\log_d N}{N}\right) \cdot (1 + l((log_d N) - 1, 1, 2)) \tag{3b}$$

We now need to compute $l(x, 1, 2)$. Similar to our computation of $L(0, 2)$, again, there are three possible scenarios. In the first case, the current node (say A) is a friend of node 2. Then the path length is 1. In the second case, there is a trail with an end point at node 2 going through node A. In this case, the mean path length is $\frac{\log_d(N)}{2}$. In the third case, the packet continues along the current trail to node 1.

$$l(x,1,2) = \frac{2\log_d N}{N} \cdot \left(\frac{\log_d N}{2}\right) + \left(1 - \frac{2\log_d N}{N}\right) \cdot (1 + l(x-1, 1, 2)) \tag{4}$$

Here, the boundary conditions for terminating the recursion are as follows:

$$l(x,1,1) = x \text{ if } 0 \le x \le \log_d N \tag{5a}$$

$$l(x,z,z) = x \text{ if } 0 \le x \le \log_d N, 1 \le z \le N-1 \tag{5b}$$

$$l(0,y,z) = L(y,z) = L(0,(z-y)) \text{ if } 1 \le y \le z \le N-1 \tag{5c}$$

Let us now compute $L(0, w)$. Consider the following two scenarios. In the first case, let the closest preceding node in node 0's routing table be node i (shortcut to $i \neq 1$). Now node i may either be a friend of node 0, in which case, the path length is $1 + L(i, w)$, or node i may be the end point of a trail going through node 0, in which case, the path length is $1 + l\left(\frac{\log_d N}{2} - 1, i, w\right)$. In the second case, there is no shortcutting, and the lookup proceeds towards the next overlay hop node 1. Thus, we have that:

$$\begin{aligned} L(0,w) = \sum_{i=2}^{w} &P(\text{shortcut to i}) \cdot P(\text{shortcut via friend}) \\ &\cdot (1 + L(i,w)) + \sum_{i=2}^{w} P(\text{shortcut to i}) \cdot \\ &P(\text{shortcut via trail}) \cdot \left(1 + l\left(\frac{\log_d N}{2} - 1, i, w\right)\right) \\ &+ P(\text{no shortcut}) \cdot (1 + l((\log_d N) - 1, 1, w)) \end{aligned} \tag{6}$$

Let us now compute the probability of shortcutting to a node i. The probability of shortcutting to node w is simply $\frac{d+2\log_d N}{N}$. The probability of shortcutting to node $w-1$ can be computed as $P(\text{no shortcut to } w) \cdot P(\text{shortcut to } w - 1| \text{ no shortcut to } w)$. This is equal to $\left(1 - \frac{d+2\log_d N}{N}\right) \cdot \frac{d+2\log_d N}{N-1}$. Similarly, we can compute the probability of shortcutting to node i as:

$$P(\text{shortcut to i}) = P(\text{no shortcut to w..i+1}) \cdot \frac{d + 2\log_d N}{N - (w-i)} \tag{7a}$$

$$P(\text{no shortcut to w..j}) = P(\text{no shortcut from w..j+1}) \cdot \left(1 - \frac{d + 2\log_d N}{N - (w-j)}\right) \tag{7b}$$

Now, given that the lookup shortcuts towards overlay hop node i, it may do so because of a friendship entry in the routing table, or a trail in the routing table. The probability that the shortcut happened via a friend entry, $P(\text{shortcut via friend}) = \frac{d}{d+2\log_d(N)}$. The probability that the shortcut happened because of a X-Vine entry is $P(\text{shortcut via trail}) = \frac{2\log_d(N)}{d+2\log_d(N)}$. Thus, we can rewrite equation (6) as

$$\begin{aligned} L(0,w) = &\sum_{i=2}^{w} P(\text{shortcut to i}) \cdot \frac{d}{d + 2\log_d N} \cdot (1 + L(i,w)) \\ &+ \sum_{i=2}^{w} P(\text{shortcut to i}) \cdot \frac{2\log_d N}{d + 2\log_d N} \cdot \left(1 + l\left(\frac{\log_d N}{2} - 1, i, w\right)\right) \\ &+ P(\text{no shortcutting}) \cdot (1 + l((\log_d N) - 1, 1, w)) \end{aligned} \tag{8}$$

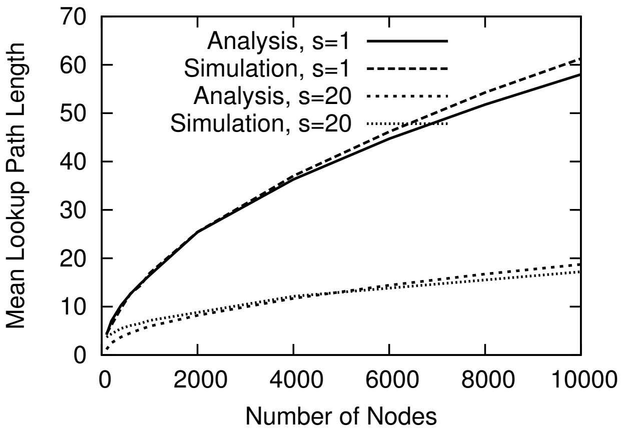


Figure 10. Validation of Analytic Model using $d = 10$

Similar to the above analysis, we can compute $l(x, i, w)$ as follows:

$$
\begin{aligned}
l(x, j, w) = \sum_{i=2}^{j+1} P(\text{shortcut to i}) \cdot \frac{d}{d + 2\log_d N} \cdot (1 + L(i, w)) \\
+ \sum_{i=2}^{j+1} P(\text{shortcut to i}) \cdot \frac{2\log_d N}{d + 2\log_d(N)} \cdot \left(1 + l\left(\frac{\log_d N}{2} - 1, i, w\right)\right) \\
+ P(\text{no shortcutting}) \cdot (1 + l(x - 1, j, w)) \quad (9)
\end{aligned}
$$

The boundary conditions for the termination of recursion are the same as in equation (5).

Validation of analytic model: Figure 10 plots the mean lookup path length as a function of number of nodes for a synthetic scale-free topology with average degree $d = 10$ using a redundancy parameter of $r = 1$. We can see that the results of simulation are a very close match with our analytic model, increasing confidence in our results. We note that our analytic model has implications for modeling network layer DHTs like VRR.

B Pseudocode

Algorithm 1 *Fwd_lookup(identifier myid, message M)*: Determines next hop for a lookup message.

```
bestroute=0
foreach element E in RoutingTable
  if distance(E.endpoint,M.dest)<
                    distance(bestroute,M.dest)
    bestroute=E
endfor
return bestroute
```

Algorithm 2 *Fwd_trailsetup(identifier myid, message M):* Determines next hop for trail path setup message.

```
bestroutes=∅
/* select all routes that make progress */
foreach element E in RoutingTable
  if distance(E.endpoint,M.dest)<distance(myid,M.dest)
    bestroutes.insert(E)
endfor
/* of these, discard (a) backtracked routes, (b) routes that
have reached bounds, (c) routes that don't make namespace progress compared to M.nextovlhop*/
foreach element E in bestroutes
  if failed_set.contains(E.endpoint,E.nexthop) or
                    (E.nexthop.numtrails > $b_n$) or
                    (numtrailsto(E.nexthop) > $b_l$) or
                    (distance(E.endpoint,M.dest) <
                       distance(M.nextovlhop,M.dest)
    bestroutes.remove(E)
endfor
/* if no remaining options, backtrack */
if bestroutes == ∅
  send_reject_to(M.prevhop)
  return
/* of remaining routes, select route with maximum
namespace progress */
routetouse=0
foreach element E in bestroutes
  if distance(E.endpoint,M.dest)<
                    distance(routetouse,M.dest)
    routetouse=E
endfor
return routetouse
```