Layer Optimization for DHT-based Peer-to-Peer Network

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***Abstract*—Hierarchical architecture has been found to facilitate effective search in P2P network and ensure system scalability in P2P application deployment. However, the lack of appropriate size ratio of super nodes layer and ordinary nodes layer makes the system search performance far from being optimal. Taking advantage of node heterogeneity, this paper presents a search delay model to characterize the two-layer P2P architecture using DHT at the top level. With the proposed models, optimal layer division can be achieved. Simulation analysis and numerical results validate the proposed model and solution.**

Keywords—Peer-to-Peer; Layer Division; Distribiuted Hash Table (DHT)

I. INTRODUCTION

With the dramatic increase of Internet bandwidth and application of Peer-to-Peer (P2P) technology in Internet telephony, VoIP (Voice over IP) technology has developed rapidly and become a very popular communication vehicle due to its low cost and convenience to Internet users. Skype[1], the perfect combination of P2P and VoIP, sets a good paradigm to inspire a generation of P2P based solutions for satisfactory real-time multimedia services over Internet. Unlike file-sharing system with multiple replications of resources, VoIP user is unique in the system, thus it is more difficult and costly to locate the exact user, whereas the fast reach to the desired user is one of the key issues to user-perceived Quality of Service (QoS). In addition, VoIP P2P infrastructure is expected to accommodate millions of users and should be well scaled owing to its possible global application. Therefore, such a P2P infrastructure has to secure the specific requirements such as low lookup delay, high hit rate, and light workload.

Current decentralized P2P networks can be generally classified into two broad categories, structured and unstructured [2]. Purely unstructured P2P systems, such as earlier Gnutella [3], tend to either cost significant overheads or generate enormous query traffic in the exhaustive search, though they are characterized as high robustness and easy maintenance, which is the key reason that they are favored in the P2P paradigm. In contrast, structured P2P networks use distributed hash table (DHT) [4,5,6,7] for accurate object placement and lookup, but they are very sensitive to the dynamics of the network [8], owing to the fact that routing efficiency in DHTs is based on the consistent maintenance of routing tables. Typically, high dynamics bring dramatically high costs. Therefore, both of systems could not scale well, neither could achieve low lookup delay and high successful hit rate. Hierarchical structure that uses DHT to organize P2P network (say Chord) in the top level may address the performance problems such as scalability and resilience, motivated by the fact that participating nodes in P2P system differ a lot in uptime, bandwidth, etc. [9].

To further exploit the hierarchical DHT and develop the best performance for VoIP application, it is critical to address the problem of effective layer division. Thus, we propose the analysis model and give out the optimal size ratio between the number of super nodes (SNs) and ordinary nodes (ONs), taking into account the metric of total search delay under the constraints of SN capacity. Our study is expected to significantly reduce the mean lookup delay and effectively facilitate large-scale deployment of DHT based P2P lookup service by providing administrative autonomy nodes.

The rest of the paper is structured as follows. Section II discusses the related work. We present the models of total search delay in Section III, and solve the optimization problem in Section IV with simulation support. Finally, Section V concludes the paper.

II. RELATED WORK

There have been some studies on the hierarchical P2P network. Garces-Erice et al. [10] explored a general framework for hierarchical DHTs, instantiating Chord at the top level. They also analyzed and quantified the improvement in lookup performance of hierarchical Chord, considering the node failure. Yuh-Jzer Joung et al. [11] presented a two-layer structure $Chord^2$ to reduce maintenance costs, taking heterogeneity into account. Their work is distinguished to other hybrid architecture in the aspect that each layer forms an individual Chord ring.

On the basis of analyzing the promising super-node based P2P network, Yung-Ming Li et al. [12] firstly investigated the issue of sizing and grouping decisions from the perspective of P2P network organizers, due to the important role they play in determining network performance. Their work mainly focused on network scale determination, and grouping decisions were mentioned as well in the context of symmetric interconnection structures: isolated, chained and complete. However, the work doesn't aim for deployment. Since P2P network is self-organized with total autonomy, it is not very practical to predetermine or design the scale of the network. Motivated by the work of Li Xiao et al. [13], we focus on studying the grouping decision to improve performance of the P2P network and thus make it scalable, taking advantage of the node heterogeneity. Our work differs from theirs on two aspects: (1)

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We study DHT based upper layer, while they focused on the unstructured upper overlay instead. (2) We optimize the scheme by considering lookup delay with the capability constraint of the super node, while they tried to make a tradeoff between workload of super node and overall P2P network. Zoels et al. [14] proposed an analytical framework to analyze the same hierarchical P2P architecture as we are studying on. They evaluated the costs of the whole network as well as each participant, in order to determine an optimal layer division of a given system, similar to the way that work [13] applied. Recently, the authors of [15,16] further presented an analytical model for DHT-based two-tier P2P overlay and determined optimal fraction of superpeers in the system, aiming at minimizing the total traffic without overloading any peer. Complementary to their work, our goal is to minimize lookup delay of the system.

III. MODELING LOOKUP DELAY

A. *Hierarchical structure model*

In the considered two-layer hierarchical architecture, the participants are categorized as Ordinary Nodes (ONs) and Super Nodes (SNs). Those with longer uptime, better process capacity, network bandwidth and storage are elected as SN from the ONs. Each SN is responsible for its cluster and connects with all the nodes in the cluster. Meanwhile, the SN participates to form DHT-based SN network to facilitate upper layer searching (refer to Figure 1).

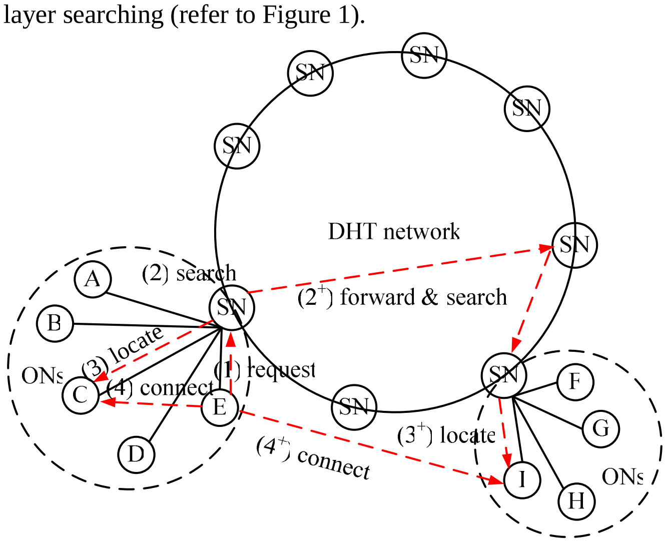

Figure 1. Search model in Hierarchical P2P network

Only the SN maintains up-to-date information on all resources (nodes in the context of VoIP) available in the cluster. Every search query is generated at one of the nodes (including SN) in the cluster, and first processed at the local SN on a first-come, first-served basis. For a specific query, SN first examines the resource in its cluster. If not satisfied, the query will be forwarded to other SNs and searched in the upper SN network. Figure 1 depicts the search operations of a hierarchical P2P network. Node E sends a query to its responsible SN. If the target node is within the cluster, say node C, SN will locate it by examining its resource list. If the query could not be satisfied in the cluster, say target node I, SN will search in the upper DHT-based P2P network (instantiating Chord in this paper). Once the desired node is located, direct connection could be established between the two nodes.

Consider a P2P hierarchical network with N participating nodes, in which N_{SN} nodes are SNs and N_{ON} nodes are ONs. Let η denote the layer size ratio, that is $\eta = N_{ON}/N_{SN}$, the number of nodes that each SN takes care of. We have $\frac{N_{SN}}{N} = \frac{1}{1+\eta}$, $\frac{N_{ON}}{N} = \frac{\eta}{1+\eta}$, which denote the ratio of the number of SNs and ONs to that of the participating nodes, respectively. Without loss of generality, we assume that all the nodes in the same category (SN or ON) are statistically identical.

In this section, we characterize the impact of layer size ratio η on probability of SN failure and then model total search delay under the constraint of available SN capacity.

B. *Probability of SN failure*

In [6], node availability is calculated by dividing the number of probes that a host responds to by the total number of probes in Overnet, which is structured on a DHT called Kademlia. According to their measurement results, assuming x is node availability, the CDF (Cumulative Distribution Function) of node availability could be well modeled by power distribution of the form x^k, where k mostly falls in the interval of (0.3,1) within normal observation period (illustrated in Figure 2).

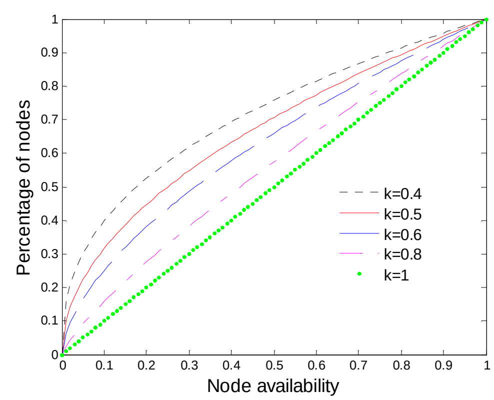

Figure 2. Node availability modeled by power distribution with varying observation time period

That is, the percentage of nodes whose node availability not exceeding value x is x^k. Equally, the percentage of nodes whose node failure exceeds value (1-x) is x^k. Given layer size ratio η, the ratio of the number of SNs to that of all the participating nodes is $\frac{N_{SN}}{N} = \frac{1}{1+\eta}$. Since SNs typically have longer uptime than ONs and therefore achieve higher node availability, we have

$$1 - \frac{1}{1+\eta} = x^k, \text{ and } x = \left(\frac{\eta}{1+\eta}\right)^{\frac{1}{k}}$$

That is, given η, the minimum node availability for an SN is $(\eta/(1+\eta))^{\frac{1}{k}}$. Accordingly, failure rate of each SN will not exceed $1-(\eta/(1+\eta))^{\frac{1}{k}}$. In the worst case, all SNs have

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failure rate $p = 1-(\eta/(1+\eta))^{\frac{1}{k}}$.

C. Modeling and analyzing search delay

In SN based hierarchical structure, search delay consists of two parts: (1) queuing delay at the SNs, (2) propagation delay during search operation, including propagation delay between ON and its responsible SN, and search propagation delay in SN overlay network. As locality-aware mechanism has been studied and widely applied in P2P paradigm [17], we can introduce locality-awareness upon ONs joining SN and the mean latency between an ON and its responsible SN $E[T_{Intra}]$ is trivial compared to the mean latency between SNs in the upper layer. As to search propagation delay, we define the metric of lookup hops in SN upper network as the hops taken from sending query to receiving response, instead of the mostly measured hops from sending query to reaching the responsible node in flat P2P network, for the sake of fair comparison. Thus, one more hop in P2P network to forward the result back would be included.

We characterize the mean lookup hops in the upper SN network in this subsection. Then we model queuing delay at an SN. Finally the total search delay is proposed.

1) Modeling lookup hops in upper SN network

Taking Chord for instantiation as the upper DHT based SN network, we quantify the mean lookup latency in Chord network according to Garces-Erice's work [10], and get the result by calculating in Matlab, as illustrated in Figure 3.

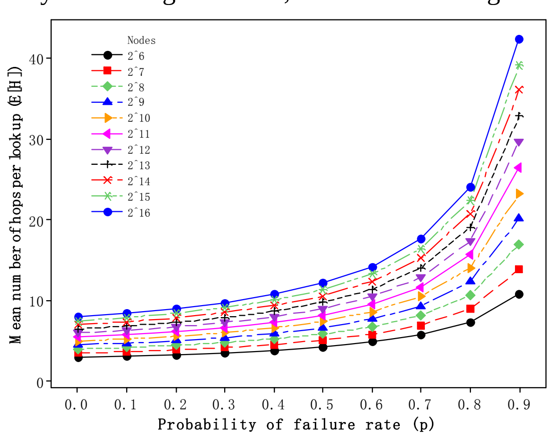

Figure 3. Mean number of hops per lookup

Let $E[hop]$ denote the mean overall lookup hops taken in the SN network, i.e. $E[hop] = E[H]+1$, where $E[H]$ is the mean lookup hops from the requesting SN to the target SN, and we add one hop for the target SN tracking back to the querying SN. $E[H]$ is obtained according to the work [10] with Chord population $N_{SN} = N/(1+\eta)$ in the upper layer.

Apparently, $E[H]$ varies with N, node failure rate p and layer size ratio η. Since failure rate p relies on η value, $E[H]$ is the function of η when N is given.

2) Modeling queuing delay at SN

Standard queuing model is applied to evaluate the delay occurring at each SN. The service time for search process at SN is assumed to follow an exponential distribution with service rate μ. Previous research [18] suggests that Poisson process is valid for modeling arrivals of user-initiated requests. Dang et al. [19] also provide evidence that VoIP call arrival forms Poisson process. We therefore assume that requests follow a Poisson process. Since requests from all the nodes are independent Poisson processes, the aggregate request arrival at an SN is also a Poisson process and the search at SN can be modeled as an M/M/1 queue.

Let f_q be the query arrival rate from each node, the aggregate requests arriving at each SN consist of those from its cluster $\lambda_i = f_q(\eta+1)$ and those forwarded traffic in the upper DHT network λ_e. The aggregate request arrival rate is $\lambda = \lambda_i + \lambda_e$. We assume that each SN shares the overall lookup workload in Chord evenly, since SNs are distributed uniformly and independently in the identifier space in light of the Chord algorithm. Thus,

$$\lambda_e = \frac{Nf_q(1-\eta/(N-1))E[hop]}{N_{SN}} = f_q(1+\eta)(1-\frac{\eta}{N-1})E[hop]$$

Where $\eta/(N-1)$ is the expected node availability within the local cluster, as the probability of the target node which the initiated node seeks for is uniformly distributed among all the participating nodes. Therefore, $1-\eta/(N-1)$ is the expected probability that the query has to be forwarded and circulated in the upper SN network. The expected sojourn time (queuing delay) at an SN is as follows

$$E[T_w] = \frac{1}{\mu-\lambda} = \frac{1}{\mu - f_q(1+\eta)(1+(1-\eta/(N-1))(E[H]+1))} \quad (1)$$

with the constraint of $\mu/\lambda > 1$.

Let $f(\eta) = (1+\eta)(1+(1-\eta/(N-1))(E[H]+1))$, then we have $f(\eta) < \mu/f_q$. We examine the derivation of $f(\eta)$, i.e.

$$f'(\eta) = 1+(1-\frac{1+2\eta}{N-1})(E[hop]) + E'[hop](1+\eta)(1-\frac{\eta}{N-1}).$$

As illustrated in Figure 3, $E[H]$ is increasing with respect to network scale. Furthermore, the increment of lookup hops with different failure rate (especially failure rate <0.5, which is easily achieved in SN upper network) is similar to that of failure free $p=0$. We assume that

$$E'[hop] \doteq \left(\frac{1}{2}\log\frac{N}{1+\eta}+1\right)' = -\frac{1}{2\ln 2(1+\eta)},$$ thus we have

$$f'(\eta) = 1+(1-\frac{1+2\eta}{N-1})E[hop] - \frac{1}{2\ln 2}(1-\frac{\eta}{N-1})$$

$$> (1-\frac{1+2\eta}{N-1})E[hop] + \frac{\eta}{N-1} > 0$$

That is, $f(\eta)$ is monotonously increasing with respect to η. For $\eta < \eta_{\max}$, where $\eta_{\max}$ is the upper bound of value η, $E[T_w] = \dfrac{1}{\mu - f_q \times f(\eta)}$ is thus monotonously increasing with respect to η as well. We can have the same result as illustrated in Figure 4, where $N = 2^{16}$, $k = 0.7$, $f_q = 1/60$, $\mu = 15, 20, 25, 30$ respectively, for instantiation.

Normally, available SN service capacity μ and request arrival rate of each node f_q are given, thus we can find upper

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bound $\eta_{\max}$, according to $f(\eta) = \mu / f_q$. Let $\eta < \eta_{\max}$, then the constraint $f(\eta) < \mu / f_q$ is satisfied. Herein, $\eta_{\max}$ is a critical parameter, as queuing delay increases sharply when $\eta \to \eta_{\max}$.

Numerical Results: Some numerical results of $\eta_{\max}$ calculation are presented as follows. Set failure parameter k=0.7, N= 2048, 8192 and 65536 respectively. We vary the value of μ / f_q to determine the corresponding upper bound $\eta_{\max}$ and the results are illustrated in Figure 5. With the identical μ / f_q, the larger the network scale, the least the $\eta_{\max}$ can be obtained, leading to the narrower interval for choosing η. As the P2P network is toward expanding dramatically over time suggested by the present P2P networks, the issue should be seriously taken into account when designing P2P network architecture or dynamically adjusting η in runtime. In addition, the upper bound $\eta_{\max}$ is increasing with respect to the value μ / f_q, which indicates that better SN capacity can enlarge the possible η value interval if the request rate is fixed.

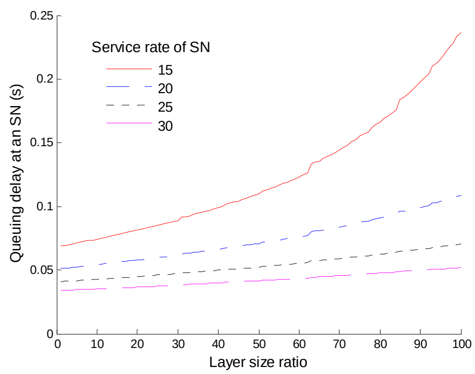

Figure 4. Queuing delay at SN vs. η with varying μ

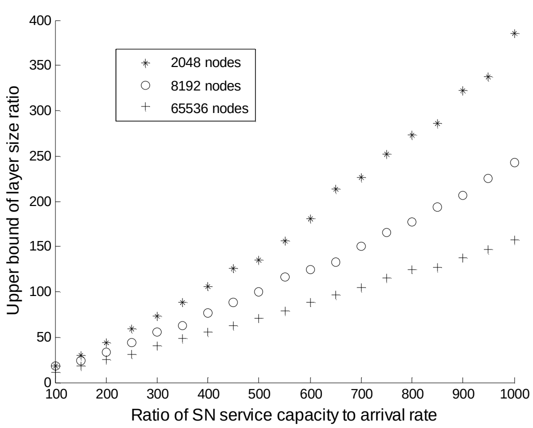

Figure 5. $\eta_{\max}$ vs. given μ / f_q

3) *Total lookup delay*

Assuming that the propagation between ON and SN within a cluster is negligible compared to the propagation between SNs, i.e. $E[T_{Intra}] \approx 0$, as ON joins SN with locality-awareness, the total mean lookup delay can be expressed as follows:

$$E[T] = \frac{\eta}{N-1} E[T_w] + (1 - \frac{\eta}{N-1})(E[T_w] + (E[T_w] + D)(E[H]+1)) \quad (2)$$

Where $\frac{\eta}{N-1} E[T_w]$ is for the query which is satisfied within the local cluster, thus total lookup delay is the queuing delay $E[T_w]$ at the responsible SN with the hit rate $\frac{\eta}{N-1}$. Otherwise, the query will be forwarded by the SN and searched in the upper SN network. In addition to the queuing delay at the responsible SN, each hop in the upper DHT search network will take $E[T_w] + D$, where D is the latency between two arbitrary nodes in the P2P network. Altogether there are $(E[H]+1)$ hops in average as aforementioned. We therefore have total lookup delay $(E[T_w] + (E[T_w] + D)(E[H]+1))$ for those searching in the external of the cluster.

Substitute $E[T_w]$ to Equation (2) and rewrite it. We have

$$E[T] = \frac{1 + (1 - \frac{\eta}{N-1})(E[H]+1)}{\mu - f_q(1+\eta)(1 + (1 - \frac{\eta}{N-1})(E[H]+1))} + D(1 - \frac{\eta}{N-1})(E[H]+1) = T_q + T_p \quad (3)$$

We define two types of delays: total queuing delay at SNs T_q and total search propagation delay T_p, which is incurred by the hopping time in the SN network.

IV. SOLUTION TO OPTIMAL LAYER SIZE RATIO

In this section, we present the optimization problem and solve the optimal layer size ratio according to the above analysis, demonstrated by numerical results in Matlab. Simulation is conducted to support the proposed model.

A. *Problem statement*

The problem of seeking for optimal layer size ratio for the hierarchical architecture is to find the optimal ratio of the number of ONs to the number of SNs, which could achieve the least total lookup time under the constraint of the available SN's capacity. That is, it is an optimization problem stated as follows:

$$\begin{cases} \min & E[T] \\ s.t. & \lambda < \mu \end{cases} \quad i.e. \quad \begin{cases} \min & E[T] \\ s.t. & \eta < \eta_{\max} \end{cases} \quad (4)$$

Herein, μ is the average available service capacity of SN. From the Equation (3), $E[T]$ is dependent of $E[H]$, μ, η, f_q and *D*. According to the previous analysis, $E[H]$ relies on layer size ratio η solely for a specific network with *N* nodes. Typically, parameters of μ, *D* and f_q are given for a specific system, so $E[T]$ is the function of η. Intuitively, we can find the optimal value of η at the minimum of $E[T]$.

B. *Solving optimal layer size ratio*

King[20] estimates RTT (Round Trip Time) between any two hosts in the Internet by estimating the RTT between their domain name servers. Since the edges in P2P network are not physical communication links, but instead only virtual links between the peers, the nodes could be geographically

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dispersed. Therefore, the latency between two P2P nodes is just as the latency between any arbitrary hosts, and we have the mean delay between two SNs in P2P network $D = 0.078$ second, by analyzing the current available data.

For specific network with given node capacity limitation, since parameters are predetermined by the system, we therefore have the optimal η value to achieve the minimum lookup delay under the constraint of SN capacity. We examine the mean overall lookup hops $E[T]$ with the varying layer size ratio η, which is the unique impacting factor if network size N is determined. Take a network with 2^{16} nodes for instance, and set typical parameter values as follows: $k = 0.7, f_q = 1/60, D = 0.078, \mu = 15$. Figure 6 illustrates the trends of the mean overall lookup delay with the varying η. Total search delay $E[T]$ decreases when η is low, while increases as η goes higher. Once η is approaching $\eta_{\max}$, $E[T]$ increases steeply as queuing delay at SNs is increasing dramatically.

In addition, we can find that SN search propagation delay $D \times E[hop]$ decreases with respect to η, and the curve of the value turns to be flatter as η increases. The reason lies in the fact that as η increases, the number of SN $N_{SN} = N/(1+\eta)$ decreases. Fewer SNs are involved in search process in the upper SN layer, leading to fewer search hops and higher search efficiency. Besides, larger η means fewer SNs, which results in better capacity and lower failure rate of SNs, further reducing lookup hops as illustrated in Figure 3. Therefore, $E[H]$ decreases with the increase of η, so does $E[hop]$.

However, the total queuing delay is dominated in the share of total lookup delay when η is large, especially in the case that available capacity is low compared with the arrival rate, the curve is more dependent on the queuing delay. While queuing delay is increasing with respect to η, and approaching infinite theoretically when $\eta \to \eta_{\max}$.

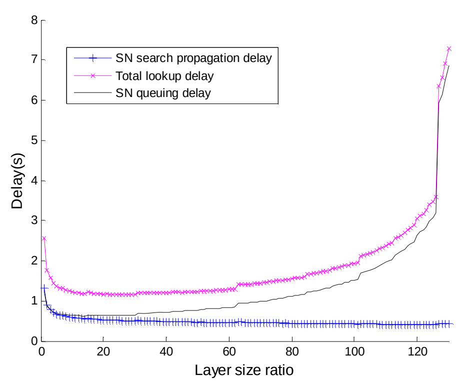

Figure 6. Delay varying with respect to η

We can find that the curve of aggregate search delay is concave and there exists a minimum value of delay with corresponding η. In this case, for example, we observe that promising η falls in the interval of [20, 50]. The optimal value is $\eta = 30$ and the least total search delay is only around 1.15 seconds accordingly, even SN is with poor capacity in this example.

It is noticeable that the curve is not smoothly decreasing as expected since a small increase can be seen when the number of SNs $N/(1+\eta)$ just exceeds a binary exponential value 2^i. The underlying reason is as follows: once the number of SNs crosses the next power of 2, the round function makes the curve incontinuous and the mean overall lookup hops slightly increase at the point.

Finally, we examined a variety of instances of parameters such as network size N, arrival rate and capacity of SN. The results keep similar, except that $\eta_{\max}$ is changing and leading to the varying scope and shift of the solution interval for the optimal η.

C. Simulation validation

In order to validate the established model, we modify and construct the two-layer P2P architecture using Chord as the top searching network based on P2PSim [21] simulation environment. In the P2P architecture, SNs are organized into Chord ring on the top layer, whereas the ONs directly connect to SNs with locality awareness. SN's available service capacity is not distinctly specified.

We tested the mean lookup delay in modified P2Psim environment with the maximum overall node population, i.e. *N*=2048 due to the limitation of the P2PSim. We set $f_q = 1/60, \mu = 10$. The simulation results of mean search delay mostly fall between SN search propagation delay and total search delay calculated by our model, as illustrated in Figure 7. Since SN capacity is not limited, the queuing delay could be very low. It is shown that simulation result can support our modeling and validate the solution.

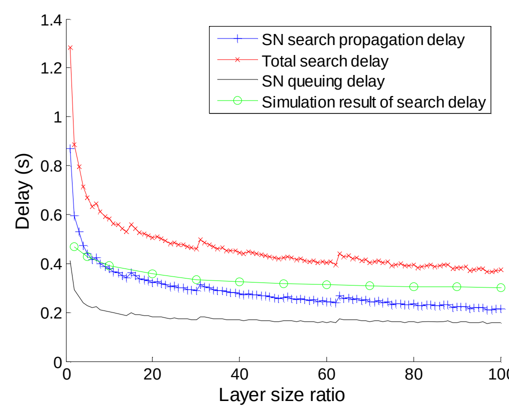

Figure 7. Simulation and modeling results of overall mean lookup hops vs. layer size ratio

V. CONCLUSION AND FUTURE WORK

Two-layer P2P organization with DHT (say Chord) at the top level is a promising hierarchy to improve performance of P2P network and satisfy numerous P2P applications, especially for VoIP deployment. This paper proposes the performance models by analyzing total lookup delay with queuing delay at SNs and propagation delay in upper DHT based searching network. Based on the models, an optimal layer size ratio can be achieved to minimize the overall lookup delay under the constraint of available SN service capacity by means of numerical results. Our simulation results support the proposed models and solutions. The crucial issues such as system maintenance and churn disposal will be studied as our future work.

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