Self-organizing Name Resolution System for ICN

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This paper proposes an algorithm to build the topology of a name resolution system for ICN in a self-organizing manner, especially focusing on low average degree of the system. Due to the self-organizing operation as well as the maintenance of low average degree, its management overhead is reduced significantly, which enables its scalable deployment. In addition, we demonstrate that the latency of the name resolution process can be reduced by 10% with our proposal compared to an existing approach that has a near optimal latency. Also, we analyze the proposed algorithm theoretically to provide a deeper understanding of the proposal.

1 Introduction

The paradigm of networking has been shifted from communication between people to content retrieval. Cisco has reported that multi-media contents would dominate up to 90% of the global consumer traffic by 2015[1]. To cope with the paradigm shift, Information-Centric Networking (ICN)[2]–[7] has gained much interest recently in network research communities[8]. One of key ICN research challenges is to design a scalable routing mechanism. In ICN, a user request is routed to the desiring data object based on its name, which is known as name based routing. A common approach to address the problem is to adopt a name resolution system (NRS) based on distributed hash tables (DHTs), which translates the identifier of data object into its locator so that the locator is used for routing a user request to the data object. For instance, CCNx[4] adopts the name aggregation mechanism that aggregates the routing entries of data objects to a prefix, e.g., a network prefix in IP. To make this approach realistic, the prefix of data object identifier should be bound to other types of identifiers for routing, e.g., the publisher or owner identifier of the data object, in order to achieve some level of aggregation under the prefix of the data object. This operation implicitly implies that the approach requires a name resolution system which binds the identifier of data object to its prefix. On the other hand, there are a group of ICN architectures which take advantage of currently deployed IP infrastructure such as NetInf[6]. Different from the previous approach, it explicitly requires a name resolution system which maps the identifier of data object to an IP address.

There are several challenges in the design of a name resolution system for ICN. First, the name resolution system is expected to support a large number of queries which include name-resolution queries from users and mapping-record-updating queries from in-network caches. For instance, users are likely to trigger multiple name resolution queries at the same time in order to browse one web-page which includes several data objects in it. In addition, due to the capacity limitation of individual in-network caches, some copies in the caches are irregularly replaced by newly appeared ones, which cause frequent updates on the mapping records in the name resolution system of ICN[9]. Second, the ICN name resolution system is expected to grow its size in a dynamic manner. The name resolution system of ICN is expected to support mapping records as many as 10^{15}–10^{22} [10]. Moreover, due to the popularity of individual data objects in different time periods, some parts of the name resolution system may grow or even shrink dynamically. Such a dynamic behavior of node participation is known as "churn" in the context of P2P[11]. With the understanding of the problems above, we propose ES *("Efficient yet Simple")* model that builds the topology of a DHT name resolution system for ICN in a self-organizing manner. Its main design goals are to achieve the low latency for mapping record lookup and low maintenance cost in a highly dynamic environment. These design goals correspond to build the topological structure of the ICN name resolution system, which has low diameter but has small average degree in the topology. Due to the low diameter, the response time to each query becomes short, which ultimately saves the network resource as well. Moreover, the small average degree simplifies the maintenance of the name resolution system, which enables it to deal with the

"churn" scenario efficiently.

This paper is organized as follows. In Section **2**, we provide the motivation of this project and review its related research. In Section **3**, we describe the proposed model including its theoretical analysis. In Section **4**, we evaluate our proposal through extensive simulations as well as theoretical analysis. Finally, we conclude this article in Section **5**.

2 Backgrounds

2.1 Motivation

This work was initiated to design the most efficient topology of a DHT name resolution system for ICN since we believe that the topology design is the kernel of the name resolution system design.

We firstly paid attention to kautz graph[12][13] which almost achieves the theoretical optimum diameter with minimum degree of individual nodes. For instance, the average distance in kautz graph is smaller than half of that in Chord[14] under the same given conditions. Also, kautz graph is known to be optimal fault-tolerance due to non-overlapping paths between origin and destination nodes. For this reason, its variations have been proposed for the topology of DHTs such as Fissione[15], Moore[16], BAKE[17], and KCube[18]. However, kautz graph has high cost of expanding its size, e.g. adding one node to the graph triggers the rearrangement of almost half of the links[19]. Although, partial line graph (PLG)[20] was proposed to deal with the problem, it still requires the update of the identifiers of individual nodes as its size expanding. This expansion problem prevents kautz graph from being used in a dynamic network environment. In summary, there are several theoretical frameworks which can build an efficient topology in terms of network distance or robustness in the given number of nodes and degree.

However, its complexity and expansion problem disable them to be adopted in a dynamic network environment.

One promising approach which achieves the efficiency without causing the complexity and expansion problems is Symphony[21]. It takes advantage of the idea of small world[22] which constructs a "*small*" distance topology using small number of links. For instance, when the number of nodes and network distance are given as conditions, Symphony can construct a topology which satisfies the conditions using only half number of links that Chord uses. However, one discouraging feature of Symphony is its estimation protocol which runs in the background of the system to estimate the system parameters. The cost of running such an estimation protocol is prohibitive as the size of the system increases, especially in designing a scalable name resolution system. We are motivated not only to overcome the discouraging feature of Symphony but also to achieve better performance even with its simpler operation.

2.2 Related works

DNS (Domain Name System) is the most widely known name resolution system. It relies on the hierarchical structure of the object identifier, which is not suitable to support a flat identifier. Also, its heavy use of extensive caching prohibits DNS to deal with fast updates of enormous binding information. For this reason, there have been several approaches based on DHT such as CoDoNS[23], SFR[24], and LISP-DHT[25]. However, they suffer from high latencies when binding information is distributed globally[26].

In ICN context, NetInf[6] has proposed two resolution schemes: Multilevel DHT (MDHT)[9] and Hierarchical SkipNet (HSkip)[27]. PSIRP[28] has chosen hierarchical Chord[29] among the many available overlay designs. For a general ICN architecture, Kostas et al. proposed hierarchical Pastry[30]. They aim to deal with the problem of the current DHT designs which overlook physical network proximity, administrative boundaries and inter-domain routing policies, or a combination thereof. However, these approaches simply make a hierarchical or modularized structure of a conventional DHT such as Chord[14] which could be optimized further. As mentioned previously, the average distance in kautz graph is smaller than half of that in Chord[14] in the given number of nodes and degree.

We argue that it is worth to pay more attention to the design of ICN name resolution system under the principle of "clean slate" instead of simply merging conventional systems because we believe that an efficient name resolution system will be the key to the success of global level deployment of ICN.

3 ES model

Figure 1 illustrates the joining process of a node in ES model. Imagine a ring of which each point corresponds to a hash value from any cryptographic hash function. Thus, each joining node produces own hash value using its unique identifier such as MAC address to find its own location in the identifier space of the ring. Once the joining node finds its location, it manages the identifier space from its own identifier to its immediate clockwise neighbor node.

The newly joining node creates two different types of links, namely short distance links (*S*) and long distance links (*L*). The short distance links are created between the joining node and its immediate neighbors. The long distance links are created following rules.

1) Long distance links: The newly joining node generates *L* number of hash values, e.g., *hash*[MAC address + 1] ... *hash* [MAC address + *L*]. Then, the joining node finds individual nodes which manage the corresponding hash value. Once each counterpart managing node is found, the managing node randomly selects one of its neighbors and passes the identifier of the neighbor to the joining node. Finally, the joining node connects to the node using the given identifier. There is a case that the joining request may be rejected due to the maximum number of links allowed for each node. In this case, the initially selected managing node becomes the end point to the joining node.

For instance, the joining node *A* in Fig. 1 finds the closest node from its location to join the ring topology which can be implemented in various ways. A flooding mechanism within a limited area or a bootstrapping server can be adopted. Then, it creates short links first between the joining node and its immediate clockwise neighbors. For each long link, the joining node *A* generates an unique identifier based on the hash value of its MAC address, and finds the node which manages the identifier, in this example, the node *B*. Thanks to the randomization of a hash function, the node *B* can be regarded as a randomly selected node in the ring topology. Once a connection is made between the node *A* and *B*, the node *B* randomly selects one node among its neighbors, in this example node *C*, and passes its identifier to the joining node. Finally, the joining node connects to the node *C* using the received identifier. The node *C* may reject the joining request due to its allowed maximum number of links. In this case, the joining node *A* selects the initially selected node *B* instead of the node *C*. In the theoretical analysis in *3)*, we assume that the joining process is repeated from the beginning when the joining request is rejected.

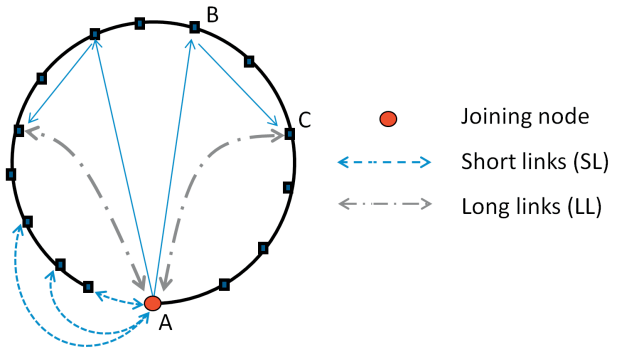

Fig. 1 ES model

2) Routing: ES model uses a bidirectional link to achieve robust and reliable operation. Since each node has its own identifier whose numerical value can be compared each other, several variations of greedy routing can be a potential candidate for our proposal. Each node simply forwards any request message to one of its neighbors in such a way that the forwarding reduces the absolute distance to the destination point. However, the focus of this paper is not routing but the construction of a topology for a name resolution system. Further work on the routing issue is in the list of our future work.

3) Theoretical analysis: Here we introduce the parameters of the proposed model, and analyze the relation between the parameters and the average distance of the topology constructed from the model. Following are the parameters of ES model.

- S: number of short links
- L: number of long links
- m: average degree (S+L)
- T: cutoff maximum degree
- AD: average distance

First, the analysis begins the derivation of the degree distribution of the topology from the model. This analysis is based on the fact that the variation of each state of a system can be described as difference between the influence tending to bring the system into the state and the influence tending to take the system out of the state. Figure 2 illustrates the evolution of node degree counts N_k as the number of nodes in the network increases. Here, N_k is the number of nodes possessing degree k. At any time, it begins with N_m since there is always at least one node with degree m in the network. Suppose that the constructed network has N number of nodes, and a new node with degree m is about to join to the network. The probability that N_{k-1} evolves to N_k due to the attachment of the new node is defined as $\boldsymbol{\Pi}_{k-m}$ shown in Equation (1).

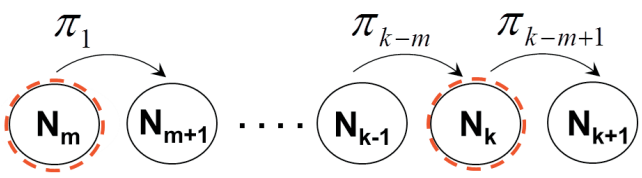

Fig. 2 State transition rate diagram showing the variation of the number of nodes with its degree

$$\Pi_{k-m} = \frac{S}{L+S}\frac{mN_{k-1}}{n} + \frac{L}{L+S}(k-1)\frac{N_{k-1}}{2n} \quad (1)$$

The first term of the right side of the equation represents the process that N_{k-1} evolves to N_k due to the random attachment governed by the parameter $S/(L + S)$ since short links in ES model are created based on the random attachment. The probability that a randomly chosen node from the network has degree k-1 is equal to N_{k-1}/N, and the probability is proportional to the parameter m since each new node makes m connections to the existing network. The lowercase n represents a time-like integer parameter since a joining node is introduced to the network in each time frame n. The n becomes asymptotically equal to N only if the n increases to infinity. The second term describes the process that N_{k-1} evolves to N_k due to the preferential attachment determined by (1-S/(L + S)). The probability that a neighbor of a randomly chosen node has degree k - 1 is equivalent to the probability that a randomly chosen link belongs to a node with degree k - 1. Thus, this probability can be obtained by dividing all links that are connected to nodes with degree k - 1 by the total number of links in the network which becomes $(k - 1)Nk\text{-}1/mN$. This probability is also proportional to the parameter m since each new node makes m connections to the existing network. Thus, cancelling out m in both the numerator and in the denominator, there is not m in the second term. To simplify the expression of equations, let us define following relation;

$$\alpha = \frac{S}{L+S} \quad (2)$$

In Figure 2, the variation of N_k due to the attachment of a new node can be defined as the difference between Π_{k-m} and Π_{k-m+1} as follows:

$$\frac{dN_k}{dn} = \frac{N_{k-1}}{n}(\alpha m + (1-\alpha)(k-1)/2) - \frac{N_k}{n}(\alpha m + (1-\alpha)k/2) \quad (3)$$

Since the total elapsed time n is equivalent to the total number of nodes in the network, N_k/n is equivalent to $P(k)$ which represents the probability that a randomly chosen node has degree k. In addition, $d N_k/dn$ also becomes $P(k)$ in equilibrium state since N_k is equal to $nP(k)$ so that $dnP(k)/dn$ becomes $P(k)$. Thus, by substituting N_k/n and dN_k/dn with $P(k)$, and N_{k-1}/n with $P(k\text{-}1)$, the Equation (3) becomes

$$P(k) = \frac{2\alpha m + (1-\alpha)(k-1)}{2 + 2\alpha m + (1-\alpha)k}P(k-1) \quad (k \geq m+1) \quad (4)$$

To complete this analysis, we define the initial condition of $P(m)$. In Figure 2, the variation of N_m due to the attachment of a new peer can be obtained by calculating the probability that individual nodes with degree m maintain its degree without gaining a link. Thus,

$$\frac{dN_m}{dn} = 1 - \Pi_1 \quad (5)$$

where Π_1 represents the probability that $N(m)$ evolves to $N(m + 1)$. Thus, 1- Π_1 represents the probability that $N(m)$ does not evolve to $N(m + 1)$ due to the joining process. In Equation (1), by substituting k with $m + 1$, it becomes

$$\Pi_1 = \alpha\frac{mN_m}{n} + (1-\alpha)\frac{mN_m}{n} \quad (6)$$

Hence, by substituting Equation (6) into Equation (5), the initial condition $P(m)$ becomes

$$P(m) = \frac{2}{\alpha m + m + 2} \quad (7)$$

Thus, we can derive the degree distribution of the constructed topology recursively from Equations (4) and (7) when the parameters of S, L, and m are given.

Based on the degree distribution derived in the previous section, the average distance AD needs to be defined as a function of the degree distribution. We here use the generating function $G_0(x)$ which represents the degree distribution of a given topology as follows:

$$G_0(x) = \sum_{k=0}^{\infty} P(k)x^k \quad (8)$$

where $P(k)$ is the probability that a randomly chosen node on a topology has degree k. Thus, the average degree of the randomly chosen node is given by

$$< k >= \sum_{k=0}^{\infty} kP(k) = G'_0 \quad (9)$$

where $G'_0(1)$ means d/dx $G_0(x)|x=1$.

To enhance the comprehension of the following derivation, Fig. 3 is prepared. Now we are interested in the degree distribution of the node (e.g., the node b or c in Fig. 3) at which is arrived by following a randomly chosen link (e.g., the link ℓ or ℓ') from the randomly chosen node (e.g., the node a), because it enables us to estimate the number of nodes within a certain number of hops from the randomly chosen node. This distribution is governed by the degree of the node which is attached to the end of the randomly

chosen link (e.g. a high degree node tends to be reached by a randomly chosen link more often than a low degree node). Thus, its normalized distribution is given by

$$\frac{\sum_{k=0}^{\infty} kP(k)x^k}{\sum_{k=0}^{\infty} kP(k)} = x\frac{G'_0(x)}{G'_0(1)} \tag{10}$$

Here, if we only consider the degree of the node (e.g., the node *b* in Fig. 3) which is reached by following the randomly chosen link (e.g., the link ℓ), especially excluding the randomly chosen link itself (i.e., the link ℓ), we need to divide by one power of *x*. Thus, it becomes

$$G_1(x) = \frac{G'_0(x)}{G'_0(1)} = \frac{G'_0(x)}{<k>} \tag{11}$$

To use of the property of the generating function, the distribution of the second neighbors of the original randomly chosen node is given by

$$\sum_{k=0}^{\infty} P(k)[G_1(x)]^k = G_0(G_1(x)) \tag{12}$$

By extension, $G_0(G_1(\ldots G_1(x)\ldots))$ can generate the distribution of *M* neighbors. Let us define the generating function $G^{(M)}(x)$ that represents the distribution of the number of neighbors that are *M* hops away from a randomly chosen node.

$$G^{(M)}(x) = \begin{cases} G_0(x) & M = 1 \\ G^{(M-1)}(G_1(x)) & M \geq 2 \end{cases} \tag{13}$$

Then, the average number of neighbors which are located at *M* th hops away from a randomly chosen node, e.g. (refer to Equation (9)), is given by

$$G^{(M)}{}'(1) = G'_1(1)G^{(M-1)}{}'(1) = [G'_1(1)]^{(M-1)}G'_0(1) \tag{14}$$

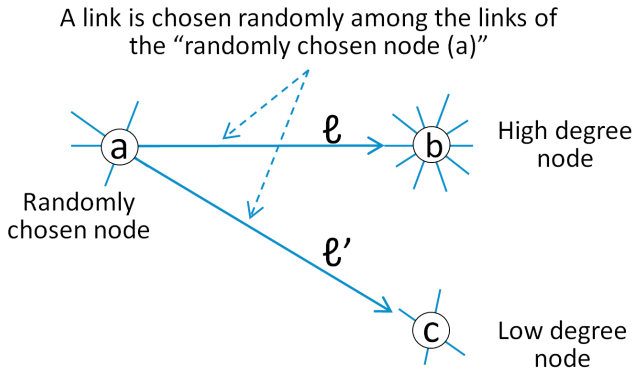

Fig. 3 Relation between the randomly chosen node a and its neighbor node b or c. The node a randomly selects its link (ℓ or ℓ') to reach to its neighbor b and c. For instance, the high degree node b tends to be reached by the randomly chosen link more than the low degree node c.

From the degree distribution shown in Equations (4) and (7) with (α=0), we obtain following expression.

$$P(k) = \frac{2m(m+1)}{k(k+1)(k+2)} \quad (m \leq k \leq T) \tag{15}$$

Then, the generating function for the topology is given by

$$G_0(x) = \sum_{k=m}^{T} \frac{2m(m+1)}{k(k+1)(k+2)} x^k \tag{16}$$

To utilize the Equation (14), we need to define $G'_0(1)$ and $G'_1(1)$ using the Equation (16). From the Equation (11), the approximation of the $G'_1(1)$ can be defined as follows;

$$G'_1(x) = \frac{1}{G'_0(1)} \frac{2m(T-m+1)}{(T+2)} \tag{17}$$

Thus, the average number of nodes which are located at *M* th hops away from a randomly chosen node in the ES topology is given by

$$G^{(M)}{}'(1) = m\left[\frac{2(T-m+1)}{(T+2)}\right]^{M-1} \tag{18}$$

where we used $<k>=m$. Now, we can define the average distance *AD* of the ES topology using Equation (18) as follows;

$$N = \sum_{M=1}^{AD} G^{(M)}{}'(1) \tag{19}$$

The average distance *AD* can be derived from Equation (18) and given by;

$$AD = \frac{\log\left[\frac{N}{m}\left(\frac{2m(T-m+1)}{T+2} - 1\right) + 1\right]}{\log\left[\frac{2m(T-m+1)}{T+2}\right]} \tag{20}$$

The optimum average distance AD_{opt} from the ES model can be found as $T \to \infty$,

$$AD_{opt} = \frac{\log\left[\frac{N}{m}(2m-1)+1\right]}{\log[2m]} \tag{21}$$

4 Evaluation of ES model and its performance

This section presents the results of simulation as well as theoretical analysis presented previously.

4.1 Average distance (AD) and cutoff max-degree (T)

Figure 4 shows the variations of the average distance (AD) in Symphony[21] and ES topologies when two different routing mechanisms are used, namely greedy routing (GD-routing) and shortest path routing (SP-routing). GD-routing is often used in DHT, which forwards a query message to the destination node by reducing its geographic distance. We introduce an additional parameter called H to the GD-routing, which represents the reachability information of H hop-away neighbors. The result shows that the performance of the proposed approach becomes superior compared to Symphony within the reasonable range of the parameter values of S, L, and H. In addition, there have been several research works regarding the GD-routing on the topology with more heterogeneous degree distribution similar to our ES topology.

On the other hand, SP-routing indicates the optimal routing performance in the given topology, which enables us to compare the proposal with Symphony without any biased view. For this reason, we use SP-routing to obtain the average distance (AD) to evaluate our proposal hereafter. Moreover, the theoretical analysis of ES model was carried out under the assumption of SP-routing. First, the result shows that the proposed approach reduces the average distance of Symphony's topology by around 10%. The latency reduction is due to the high degree nodes which each node uses as hub nodes to reach the other node. Also, the theoretical and numerical results are well matched, which verifies the accuracy of the previous theoretical analysis shown in Equation (21).

Figure 5 plots the average distances of the topologies which are constructed from Symphony and the proposal as a function of the cutoff maximum degree T. As explained, the average distance decreases as the cutoff maximum degree T increases for both cases. Regarding to the parameter L, we observe that the average distance is inversely proportional to the parameter L since it represents the average degree of the topology. Another interesting point here is that increasing the number of long links L from 1 to 2 reduces the average distance significantly. However, the latency reduction due to the successive addition is not impressive.

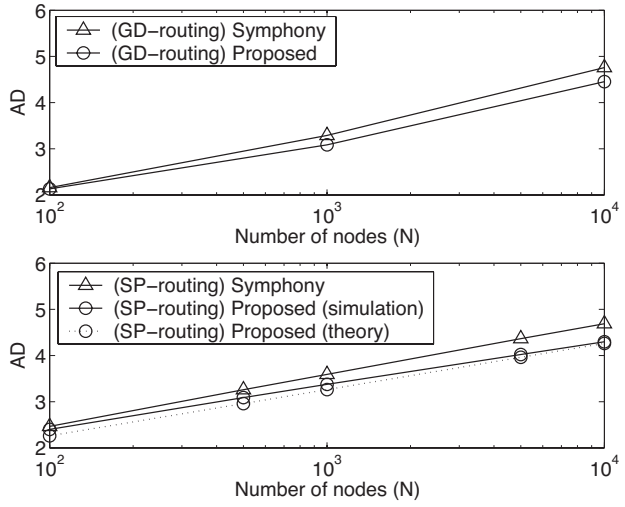

Fig. 4 Average Distance (AD). Top: Greedy Routing (GD-routing) with (H=3, S=3, L=3). Bottom: Shortest Path Routing (SP-routing) with (T= infinite, S=1, L=3). The average degrees of the proposed ES and Symphony are same for both cases (6 (GD-routing) and 4 (SP-routing) = S+L). Each point of the simulation results represents the average of 10 realizations.

4.2 Determination of cutoff max-degree (T)

While Symphony requires an estimation protocol to determine its system parameters, the ES model does not intend to operate such an estimation protocol running in the background. For doing that, one critical system parameter of ES model is the cutoff maximum degree T. This parameter is set to each node, which limits its maximum degree.

Figure 6 plots the average distances of the topologies from ES model. The theoretical analysis well predicts the variations of the average distance as a function of the cutoff maximum degree T in different sizes of the topologies. Finding an acceptable cutoff maximum degree T from the figure can be carried out by setting the differentiation of Equation (20) to a certain value, e.g. $\partial AD/\partial T = -1$.

Figure 7 shows a case how the cutoff maximum degree

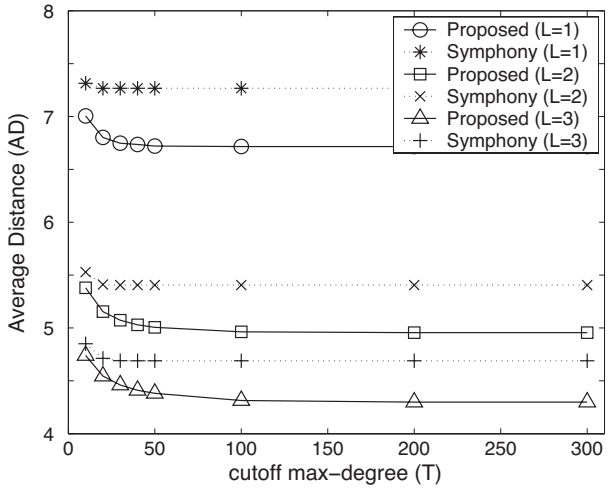

Fig. 5 AD of the topologies from ES model (N=104, S=1) and Symphony

T can be defined based on the developed analytical model shown in Equation (20). The top figure shows the cutoff maximum degree which increases the optimal average distance (T=*1*) by 10%. The bottom one shows the corresponding average distances at the cutoff maximum degrees on its top figures. From the figure, it is noticed that the average distance *AD* is not sensitive to the cutoff maximum degree *T* as well as the number of long links *L*, which enable us to set the upper-bound of these values in a deterministic manner. For instance, by setting the cutoff maximum degree *T* and the number of long links *L* to around 100 and 24 respectively, the expected maximum average distance of the ES topology with 10^{22} nodes becomes fewer than 30 hops. For a comparison purpose, Chord[14] requires $(log2N) \approx 73$ outgoing links for each node to support a topology with 10^{22} nodes, which results in the average distance of around 37 (73/2).

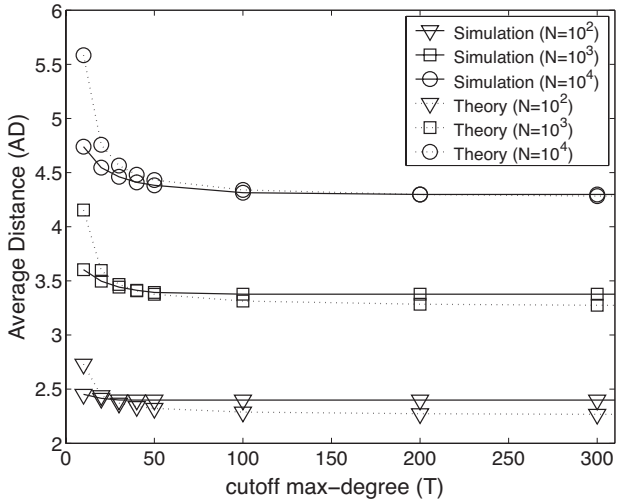

Fig. 6 AD topologies from ES model by simulation and theoretical analysis (S=1, L=3)

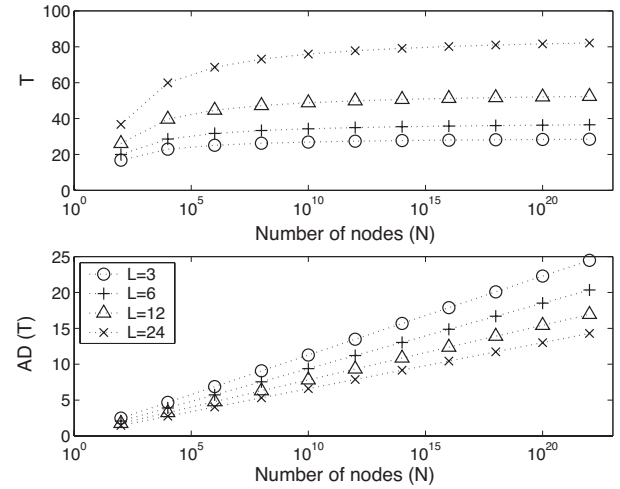

Fig. 7 Average Distance (AD). Top: the cutoff maximum degree which increases the optimal average distance (T=infinite) by 10%. Bottom: the corresponding average distances at the cutoff maximum degrees on its top figures.

5 Conclusion

This paper introduced the ES model which builds the topology of a DHT name resolution system for ICN. We demonstrated that the proposed model can reduce the average distance of Symphony by around 10% although the operation is simple since it does not need to run the estimation protocol in the background. Moreover, the theoretical analysis enabled us to comprehend the detail behaviors of ES model even in an extremely large-scale scenario.

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