A caching miss ratio aware path selection algorithm for Information-Centric Networks

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***Abstract*—In Information-Centric Networks (ICN), contents are cached on some intermediary routers. This creates thus a new situation which is totally different from the traditional path-selection paradigm: the source/destination paradigm no longer exists; instead, the new paradigm is how to find a path through a selected group of caches, so that the content is delivered via the shortest way. This paper addresses this issue and proposes a path-selection algorithm taking into account both the caching capability of router and the more traditional link cost between routers. We formulated the problem as a convex optimization problem (named ESP) which aims to get expected shortest path (ESP) by minimizing the transportation cost. By applying the Lagrangian dual theorem, we solved the ESP problem and obtained a criterion for request (and reversely, data) routing. Based on this path-selection criterion, we provide a fully distributed distance-based ESP algorithm that enables routers maintain routes to nearest content, without knowing a network topology and the caching miss ratio of content at other routers. Simulations confirm the efficiency of our approach versus the traditional shortest path algorithm.**

I. Introduction

With the popularity of digital multimedia application over Internet, the amount of digital contents is growing exponentially. The Information Centric Networking (ICN)[1] has been proposed as a promising breakthrough which provides network-embedded cache. In ICN, instead of a single source, each intermediary cache-embedding router may be a content holder. This is a totally new, and disruptive, routing paradigm versus the classical bipolar (source/destination) routing paradigm. The problem is no longer how to find the Shortest Path linking the source and the destination, but rather how to find a path through a *selection of cache nodes*, such that the request can hit a cache as close as possible to the user. We term this problem as "Expected Shortest-Path" problem.

As an example, let us consider the situation of Fig. 1. The upper path is the one computed by the classical Shortest-Path algorithm, by considering the provider as the unique source. The lower path goes through routers which are potential proxy-source. Hopefully, one of them can act as a cache, thus the lower path should have a shorter expected path. From this perspective, the routing problem in ICN has to be revisited:

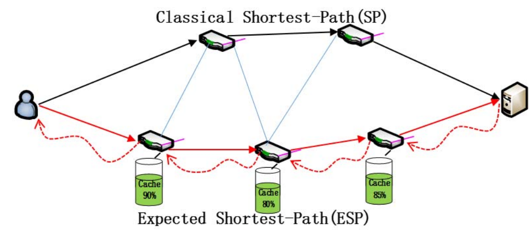

Fig. 1. The percentage in this figure denotes the cache hit ratio of the content at local router. The expected shortest path(ESP) compared with the classical shortest path(SP).

the classical Shortest Path (SP) routing algorithms, such as those in NLSR [2] and DCR [3], is no more suitable for ICN. The set of potential caches, characterized by their respective hit-probabilities, must be taken into account.

In this paper, we study this new path selection problem, and further formulate this new problem (named ESP) within a network with cache-embedding routers, with the objective of finding an optimal path to minimize the expected transportation cost. By applying the Lagrangian Dual theorem, we optimally solve this problem and obtain a new ESP routing criterion which jointly consider the link cost (as in the classical routing problem) and the content miss ratio (which is specific to ICN). What's more, we propose a fully distributed distance-based ESP algorithm which has lower communication complexity, based on the ESP routing criterion. The main contributions of this paper can be summarized as follows:

- We firstly formulate a path-selection problem as a convex optimization problem (named ESP), and then solve this problem.
- We provide a fully distributed distance-based ESP routing algorithm that allows router to choose its current optimal next-hop toward nearest content, without knowing a network topology and the caching miss ratio of content at other routers.

The rest of the paper is organized as follows. In Section II, related works are mentioned briefly. Then, in Section III, we formulate the Expected Shortest-Path (ESP) problem as a convex optimization, and then solve this problem. In Section IV, a fully distributed distance-based ESP routing algorithm is provided. In Section V, we validate our approach in ndnSIM

This work was supported by National Natural Science Foundation of China under contract No. 61471009 and Culture Development Funding under Grant No.2016-288.

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DOI 10.1109/LCN.2017.48

simulator. At last, we conclude the paper in Section VI.

II. RELATED WORK

There are many research works [2–5] which deal with the routing issue in ICN. Next, we analyze and summarize some representative approaches.

NLSR [2] and DCR [3] are representative works of topology-based shortest path algorithms. NLSR[2] presented the design of Named-data Link State Routing (NLSR) protocol, which is a link-state protocol similar to OSPF – link state advertisements are propagated throughout the entire network and each router builds a complete network topology. In DCR[3], the authors have introduced the Distance-based Content Routing (DCR) protocol, which enables routers to maintain approximate shortest path to the nearest instances of the content, and establish content delivery trees over which all or some instances of a content can be contacted. However, both NLSR[2] and DCR[3] applied traditional shortest path algorithms, which only take into account the traditional link cost between routers.

In contrast to NLSR [2] and DCR [3], PBR[4] and CAR[5] present cache-aware path-selection algorithms taking into account the caching capability of the network. PBR[4] proposed the Potential Based Routing (PBR) algorithm, which navigates a data packet within a potential field defined in the network to facilitate "routing" towards a desired location. In CAR[5], the authors also presented the problem of how to calculate the paths with the minimal transportation cost based on the caching capabilities of the network, and proposed a cache-aware routing scheme based on a solution to this minimal transportation cost problem. However, routing algorithms proposed by PBR[4] and CAR[5] have to know all other cache nodes' specific informations, such as potential value or cache hit ratio of each node, so that both of them have high communication overhead, thus they are not suitable to be implemented in practice.

Based on the analysis of the above studies, we propose in this paper a fully distributed distance-based ESP algorithm, which is more suitable for ICN.

III. REQUEST ROUTING REVISITED

A. Expected Shortest Path Problem

For simplicity, we focus on path selection problem of one single request for target content. Let p_i denote the cache miss ratio of the target content at node i, where $0 \le p_i \le 1$ for each router i, and $p_s = 1$ for subscriber s and $p_t = 0$ for producer t.

We model ICN as an undirected graph $G(\boldsymbol{V}, \boldsymbol{E})$, where $\boldsymbol{V}$ is the set of vertexes, and $\boldsymbol{E}$ is the set of arcs. Let $c_{ij} > 0(\forall(i,j) \in \boldsymbol{E})$ denotes link cost on arc (i,j). The problem of how to find an expected shortest path (from s to t) to forward subscriber' requests to hit the content, in terms of minimizing expected transportation cost, is named as Expected Shortest Path (ESP) problem. Based on these assumptions, the ESP problem, which is a convex optimization problem, can be formulated as follows:

$$
\begin{aligned}
\text{Minimize } & \sum_{\forall(i,j)\in\boldsymbol{E}} c_{ij} f_{ij} \\
\text{Subject to: } & \sum_{\forall j\in\boldsymbol{V}} f_{ji} p_i = \sum_{\forall k\in\boldsymbol{V}} f_{ik} \quad \forall i \in \boldsymbol{V} && (1)\\
& \sum_{\forall i\in\boldsymbol{V}} f_{is} = 1 && (2)\\
& f_{ij} \ge 0 \quad \forall(i,j) \in \boldsymbol{E} && (3)
\end{aligned}
$$

where $f_{ij} \in R^{+}(j \ne s)$ is a directional decision variable denoting the probability of this request flowing over edge (i,j). The constraint (1) denotes the conservation of request's probability flow on each node $i \in \boldsymbol{V}$.

B. Lagrangian Dual Problem

We solve the ESP problem by applying Lagrangian Dual Theorem. Constraints (1) and (3) can be incorporated into the objective function by associating a Lagrangian multiplier ν_i and λ_{ij} with constraint (1) and (3) respectively, then we obtain Lagrangian Dual Model (LDM) as follows:

$$
\begin{aligned}
\text{Maximize} \quad & \nu_s p_s + \inf_{f_{ij}} \left\{ \sum_{\forall(i,j)\in\boldsymbol{E}} (c_{ij} - \lambda_{ij} + \nu_j p_j - \nu_i) f_{ij} \right\} \\
\text{Subject to:} \quad & \lambda_{ij} \ge 0 \quad \forall(i,j) \in \boldsymbol{E} && (4)
\end{aligned}
$$

Moreover, if and only if $c_{ij} - \lambda_{ij} + \nu_j p_j - v_i = 0$ for all arcs $(i,j) \in \boldsymbol{E}$, the LDM(4) is feasible. Thus, the LDM(4) can be simplified as follows:

$$
\begin{aligned}
\text{Maximize} \quad & \nu_s \cdot p_s \\
\text{Subject to:} \quad & \nu_i - \nu_j p_j \le c_{ij} \quad \forall(i,j) \in \boldsymbol{E} && (5)
\end{aligned}
$$

C. ESP Criterion Derivation

In connected network, each vertex may has more than one incoming edge, so a feasible solution value ν_i of every vertex $i \in \boldsymbol{V}$ has to satisfy $\nu_i \le \min_{\forall j\in\boldsymbol{V}} \{c_{ij} + p_j \nu_j\}$ such that ν_i $(i \in \boldsymbol{V})$ can satisfy constraint (5) of the simplified LDM. To maximize $\nu_s \cdot p_s$, the optimum solution $\hat{\nu}_i(i \in \boldsymbol{V})$ need to satisfy that $\hat{\nu}_i = \min_{\forall j\in\boldsymbol{V}} \{c_{ij} + p_j \hat{\nu}_j\}$ for each node $i \in \boldsymbol{V}$.

Let $d_i = \nu_i p_i (i \in \boldsymbol{V})$ denotes an expected distance of a cache path starting from node i to the content. A set of Expected Shortest Path (ESP) formulas that solves ESP problem optimally is derived as follows

$$
\begin{cases}
d_t = 0 \\
d_i = p_i \cdot \left(\min\limits_{\forall j\in\boldsymbol{V}} \{c_{ij} + d_j\} \right) \quad \forall i \in \boldsymbol{V} - \{t\}
\end{cases}
\qquad (6)
$$

The Eqn.(6), suggests a new criterion for request (and reversely, data) routing which is quite different from the classical one, by considering jointly the (classical) link cost and the (ICN-specific) cache miss ratio. In the rest of this paper, it will be the criterion we use in our distributed, Bellman-Ford flavor, routing algorithm.

We can already notice here that d_i can be smaller than the d_j of all of its neighbors j based on Eqn.(6). Thus, by using Eqn.(6), the ESP routing will meet problem similar to negative-weight edge in Bellman-Ford, in other words, rings may occur. In our implementation, a loop-avoidance mechanism is presented in Section IV-B.

IV. Distributed Distance-Based ESP routing Algorithm

We denote a set of contents by $\boldsymbol{M}$. For each node, say i, its lexicographic value is denoted by $|i|$, the set of its neighbors is denoted by $\boldsymbol{N}_i$, the cache miss ratio of the content $k \in \boldsymbol{M}$ at node i is denoted by p_i^k, the current expected distance from node i to content k is denoted by d_i^k, the current expected distance (storing at node i) from neighbor $j \in \boldsymbol{N}_i$ to content k is denoted by d_{ij}^k, the set of current valid next-hops (related to content k) of node i is denoted by $\boldsymbol{S}_i^k$.

Based on routing informations (containing d_{ij}^k) storing at router i reported by neighbors $j \in \boldsymbol{N}_i$, router i periodically updates its distance d_i^k to content k as follows:

$$d_i^k = p_i^k \left(\min_{\forall j \in \boldsymbol{N}_i} \{c_{ij} + d_{ij}^k\} \right). \tag{7}$$

Therefore, neighbor router $h \in \boldsymbol{N}_i$ become a current optimal next-hop toward content k if and only if it satisfies the condition: $|h| = \min_{\forall j \in \boldsymbol{S}_i^k} \{|j|\}$, where $\boldsymbol{S}_i^k = arg \min_{\forall j \in \boldsymbol{N}_i} \{c_{ij} + d_{ij}^k\}$. This condition states that not only the distance passing through h from node i to content k is the smallest, but also h has the smallest lexicographic value among all the neighbors reporting the same shortest distance.

A. Routing Tables

In order to enable each router maintain current optimal routes to contents based on distance-based ESP algorithm, each router mainly maintains two tables which are ***FIB*** and ***PT*** locally, and periodically updates them.

1) Forwarding Information Base $(\boldsymbol{FIB}_i)$ stores routing informations consisting of : a) each listed content k's name, b) router i's current optimal next-hops related to content k, and c) router i's current expected distance d_i^k related to k.

When router i's current expected distance d_i^k have been changed, it will periodically send routing update informations, mainly consisting of content k's name and its currently updated distance d_i^k, to all of its neighbors.

2) Probability Table $(\boldsymbol{PT}_i)$ stores each content k' name and cache miss ratio p_i^k at local router i.

In order to compute and update the caching miss ratio p_i^k regarding content k in $\boldsymbol{PT}_i$, each router i periodically calculates the ratio of the number of incoming requests for content k (which is satisfied locally by router i) , with the total number of incoming requests for k at router i. The initialization (upon reception of the 1st request of the content k) is done with p_i^k set to 1.

B. Infinite-loop Avoidance

As analyzed in previous section, loops may occur. To avoid loop, we use the ICN node's native infinite-loop avoidance mechanism [6]. This mechanism works as follows: request (Interest) packet contains a random nonce value based on Interest packet's design [6], so that duplicates of request packet with the same nonce received by router over a loop are discarded. Therefore, when a request is unsatisfied unfortunately by routers following an ESP path with loop, and forwarded back to a router which has already received this request with the same nonce [6], it will be discarded, instead of being forwarded in this loop infinitely. Consequently, user will reissue this request again.

V. Simulation Results

In this section, based on the ndnSIM[7], we mainly evaluate the performance of ESP with the shortest path (SP) algorithm which is applied in NLSR and DCR, in terms of the hit distance which represents the number of hops a request has to travel to find the desired content. Besides, we set a blank control test with the shortest path (SP) algorithm applied to network without in-network caching capability.

A. Experimental Conditions

For what concerns the main topology of real world, we simulate the GEANT network [8], composed by 40 content routers with a diameter of 7 hops. As largely done in the ICN literature [9], contents are characterized by a Zipf-like probability distribution, and popularity values of contents are computed according to a Zipf law with parameter α.

In order to compare the performances of both ESP and the traditional shortest path algorithm under different experiment environment, we set three different test scenarios which contains 1) different popularity distributions value of content; 2) different amounts of subscriber nodes; and 3) different topologies, generated by ASHIIP v.3 [10] following the GLP model [11] ($m_0 = 20$).

In our tests, we use a catalog of 10^4 unique contents, which are supposed to have a geometrically distributed size, with an average size of 100 chunks, the cache size is fixed to 10^4 chunks[9]. The Least Recently Used (LRU) strategy is used to be a strategy of cache replacement in our tests. Each subscriber node is attached to a content router randomly. Every subscriber issues requests for different kinds of content 50 times each second in each simulation which runs 20 seconds.

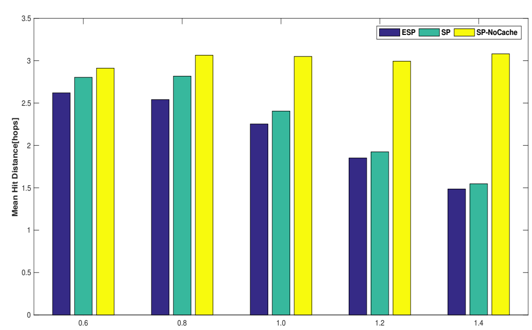

Fig. 2. Comparison of mean hit distance under different α when the number of subscriber nodes attached on GEANT topology is 15.

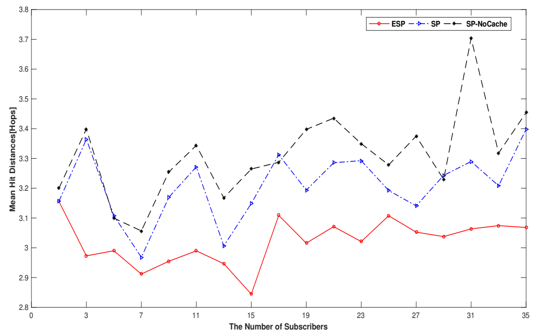

Fig. 3. Comparison of mean hit distance under different number of subscribers attached on GEANT network when $\alpha = 0.4$

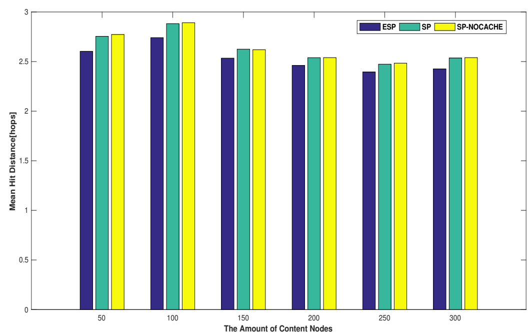

Fig. 4. Comparison of mean hit distance under different network topology when the number of subscribers is fixed as 25 and $\alpha = 0.4$

We average the results of ten runs for these three forwarding strategies respectively under each test scenario.

B. Result and Analysis

1) Impacts of content popularity distributions: As Fig.2 shows, as content's popularity α increases, both of mean hit distances decrease, which are generated by ESP and SP respectively, while those of SP without caching shows no obvious change. However, mean hit distance generated by ESP is always less than those of SP regardless of the popularity value α. This is mainly because SP algorithm aims to find the traditional shortest path to source node in ICN, without taking into consideration the in-network caching capability.

2) Impacts of the number of subscriber nodes: In order to take full advantage of every content router's caching capability and forwarding capability, we set multiple subscriber nodes in our simulation. As Fig.3 shows, the mean hit distance generated by ESP is always less than those of SP regardless of the number of subscriber nodes.

3) Impacts of topology: Fig.4 shows comparison of mean hit distance generated by ESP and SP algorithm under different network topologies in the test scenario 3. As Fig.4 shows , ESP always has better performance than the two other forwarding strategies under different topologies.

VI. Conclusion

The information-centric network, with its inherent content cache system, creates new routing paradigm. Actually, the content source is no longer unique, but is constituted by a constellation of cache-capable routers pervasively located over the whole network. This paper addressed this challenging issue by proposing a new routing algorithm with a routing criterion taking into account not only the link cost, but also the cache-miss ratio. This criterion is derived from an optimization problem (ESP) which minimizes the overall expected transportation cost. We provide a fully distributed distance-based ESP routing algorithm which is more suitable for ICN, without any knowledge of neither the topology nor the miss ratio at other nodes. Simulation results validated our design goal and confirmed the efficiency of our routing algorithm.

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