Network Resource Planning for Minimizing VRTT based on Cost Constraint

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***Abstract*—Estimating and building a reasonably sized and configured ICN network based on user needs is an important part of advancing the further implementation of ICN. Reasonable network resource planning can provide a reference for operators, give clients better use experience under certain costs. Research has so far studied planning methods for IP networks, and there is almost no method on ICN network planning.**

In this paper, we model the ICN network resource planning problem. We determine the optimization objectives and constraints, improve the accuracy of the tree topology network model based on the Che approximation, and then obtain the approach to the planning problem. Simulation experiments show that our network planning approach can effectively reduce VRTT under cost constraints, as well as the improved model is more accurate.

***Index Terms*—Information-Centric Networking, Network Planning, Caching**

I. INTRODUCTION

With the advent of Information Centric Networking (ICN) [1], the network evolves from a simple interconnection of pipes and buffers, and rather becomes a network of caches [11]. In ICN, caching is deployed in the network nodes, not just in the server. In this way, when a user requests content, the content request can be fulfilled either at the local cache node or on its way to the server, which effectively improves network performance, relieves network stress and enhances user experience.

In the MBB(Mobile Boardband) era, the global telecom ICT(Information and Communications Technology) operators are facing intense competition. On the one hand from rival competitors, and on the other hand, OTT(Over The Top) services are gaining popularity. Under these circumstances, the operators' opex and capex pressure increasingly become obvious. The operators are no longer looking at the network planning as an independent link, but incorporating it into the complete operating process in the network life cycle management, hoping to effectively decrease the total cost of ownership and building a quality network to provide for a good quality of end-user experience. But the existing research on ICN networks is only to analyze, model, and calculate the various properties of ICN.

The traditional study of network planning mainly focuses on reasonable deployment planning by combining theory and experience with the demand and scale of actual scenarios under TCP/IP network. And there are still many issues and challenges due to the large-scale deployment of networks with ICN-like architectures [12], which make traditional information statistics and information abstraction methods based on existing network topologies not applicable to the resource estimation and construction for ICN networks.

For this issue, we consider the placement of caches for minimizing investment by realizing an optimal trade-off of cache memory for network bandwidth [8]. We assume ongoing tussles between operators and content providers have been resolved so that all stored content can indeed be cached. This implies the network offers content providers the necessary control over content delivery, for billing, accounting, or ad placement, say, so that there is no impediment to delivering a content item from a remote cache if available. In modeling the network planning problem as an optimization problem, a new constraint is naturally obtained, namely the accuracy of the network model. The more accurate the network model, the

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greater the reference value of the optimization results to the actual problem. We improve on the existing network model to obtain a more accurate ICN tree topology network model.

In the remainder of this paper, we overview related work in Sec.II. Then in Sec.III, the planning problem is described, performance metric and constraint are defined, and an improved network model is presented to prepare for subsequent problem solving. Sec.IV then explores resource estimation method and parameter optimization idea, the planning problem has so far been explained from description to solution. Finally, Sec.V validates the above model and problem solving idea by simulation.

II. RELATED WORK

A. ICN Network Resource

Network storage and bandwidth resources are two important resources in Internet architecture. Optimizing the allocation and deployment structure of resources and improving the utilization of network resources is a continuous concern for network technology development. Most of the current studies on cache resource allocation in ICN networks follow the assumption proposed by Jacobson [13] that the cache is provided by routers equipped with content storage. Its capacity is limited due to technical and cost constraints. Therefore, most of the related research content uses various optimization goals or collaborative caching strategies to best utilize the overall storage capacity.

[14] proposed a cache resource allocation algorithm with the goal of minimizing user energy consumption, which optimizes the allocation of cache resources to closer users to form a network with minimal latency and energy consumption. [15] proposed a caching decision model with node cache hit variance minimization and request latency minimization as the objectives to rationally allocate resources through a heuristic algorithm with thresholds. [16] defined a new metric, request impact degree (RID), and a network heterogeneous allocation scheme for content storage space based on RID. There is no research to improve the utilization of network resources from the perspective of network resource planning.

B. ICN Cache Network Model

Network modeling is the calculation of the performance of a network given its configuration and structure [4], accurate models can guide planning. Cache hit rates are derived using the approximation introduced by Che [2] and shown by Fricker [3] to be extremely accurate. Che et al. first introduced the concept of characterized timeτ, which decouples the correlation between contents and allows the model to be used to analyze cache modeling problems. It is assumed that 1) τ is an independent constant for any given node k and content i, 2) τ remains constant for any content i at the same node. These two assumptions simplify the analysis of cache network modeling.

$$\sum_{i=1}^{N}(1 \quad e^{\ \lambda(i)\tau}) = C \tag{1}$$

$$hp = 1 \quad \sum_{i=1}^{N} q(i) e^{\ \lambda(i)\tau} \tag{2}$$

$$q(i) = \frac{c}{i^{\alpha}} \tag{3}$$

where c is the normalization factor, which aims to make the sum of the popularity of all content to 1, thus $1/\mathrm{c} = \sum_{j}^{N} 1/j^{\alpha}$. The modeling of a single node cannot meet practical needs. The cache nodes directly connected to the user are called edge nodes, and the other cache nodes between the edge nodes and the repository are called parent nodes. One of the difficulties in modeling the cache network structure lies in the calculation of the parent node cache hit rate. Based on the Che approximation, there are many modeling studies on the ICN cache networks. Giovanna Carofiglio et al. [5] have proposed a new method for calculating cache node hit rates:

$$\log p_l(i) = \prod_{j=1}^{l \ \ 1} \left(\frac{x(j+1)}{x(j)} \right)^{\alpha} p_j(i) \log p_1(i) \tag{4}$$

Where i is the content i, l is the number of layers of the node to be sought, p_1(i) is the miss probability of the content i in the edge node, p_l(i) is the miss probability of the content l in the node to be sought, and x(j) is the cache size of the layer j node. This calculation is very simple but only applicable to linear topology as well as symmetric binary tree topology.

[7] analyzed the LRU replacement strategy [10] for caching, proposed a heuristic model for cache network structure, and a linear topology is computed and analyzed with good results.

TABLE I
NOMENCLATURE

Notations	Meaning
α	parameter of Zipf distribution
N	number of content items
C	cache size of node
τ	characteristic time of node
$q(i)$	content popularity of content i
λ	total content request rate of node
$\lambda(i)$	content request rate of item i
hp	hit probability of node
mp	miss probability of node
$\mu(i)$	content miss rate of content i
t_l	round-trip time delay between leaf node and level-l
t_p	propagation delay
t_{tr}	transmission delay
t_{qtr}	transmission delay of request
t_{ctr}	transmission delay of content
$VRTT(i)$	virtual round-trip time for content i
$aVRTT$	average virtual round-trip time

III. PLANNING PROBLEM MODEL

In this section, we take VRTT(Virtual Round Trip Time) as performance index and take operation cost as constraint condition respectively. In addition to this, we take the improved cache network model as the implicit constraint of the planning problem, establish the relationship between the cost and the performance index.

A. Optimization Objective

First, we determine the performance metric. ICN can significantly reduce the amount of traffic in the network, and the most popular content can be stored on caching nodes as close to the user as possible. So we can target VRTT [9] as an optimization to efficiently describe the response process of user requests and reflect the traffic in the cache network. The formula for calculating the virtual round-trip time for content i is given below:

$$VRTT_i = \sum_{l=1} t_l \quad \left(\prod_{j=1}^{l\quad 1} mp_j(i) \right) \quad hp_l(i) \tag{5}$$

$$t_l = l \quad (2t_p + t_{qtr} + t_{ctr}) \tag{6}$$

In (6), t_{qtr} is calculated from the ratio of the packet size of the request to the maximum bandwidth, t_{ctr} is calculated from the ratio of the content item to the maximum bandwidth. In comparison, t_{qtr} is negligible, so it can be simplified to (7):

$$t_l = l \quad (2t_p + t_{ctr}) \tag{7}$$

When studying the entire network, it is not possible to focus only on the VRTT of individual content, but rather we should consider the aVRTT(average Virtual Round Trip Time) weighted by all content items, as shown in (8).

$$aVRTT = \sum_{i=1}^{N} VRTT_i = \sum_{i=1}^{N} \sum_{l=1} t_l \quad \left(\prod_{j=1}^{l\quad 1} mp_j(i) \right) \quad hp_l(i) \tag{8}$$

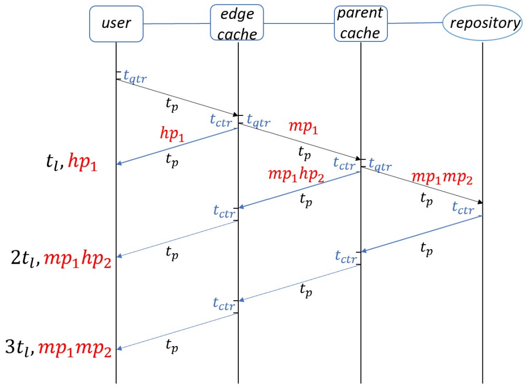


Fig. 1. Virtual Round Trip Time (VRTT)

B. Constraints

Having identified the performance metric, we also need to determine the cost of network resources. The cost of caching can be the cost of purchasing storage when the caching node is installed or the cost of operating after the completion of the network build. Bandwidth cost can be the cost of installation when configuring a network, limiting bandwidth size but not traffic, such as a wired network. It can also be a usage cost that is essentially unlimited in bandwidth size but billed on a per-traffic basis. All of these costing methods can find their counterparts in real-world scenarios, which we summarize as building cost and operating cost. Here we study the operating costs and define the cost formula(in a two-layer tree topology):

$$Cost_{operate} = \mathrm{T}(1 \quad \theta) \quad (k_b + k_s) + (\mathrm{MC} + C_2) \quad k_m \tag{9}$$

where $Cost_{operate}$ denotes the total cost, T is the maximum bandwidth size, θ is the edge node hit probability, and k_b is the traffic cost in U/MB, k_s is the cost of content service in U/MB, M is the number of edge nodes, C is the size of the edge node cache. C_2 is the size of the parent node cache and k_m is the cache operating cost in U/MB. k_s compared to k_b whereas, it is negligible and can therefore be approximated as k_s + $k_b \quad k_b$. In the planning problem model, the cost needs to be less than or equal to a given constant.

C. Improved Cache Network model

There are many topologies of cache networks, such as linear topology, tree topology, and graph topology. Here we study linear topology and tree topology, which are the topologies often used in access ISP. The cache network structure is shown in Figure 2.

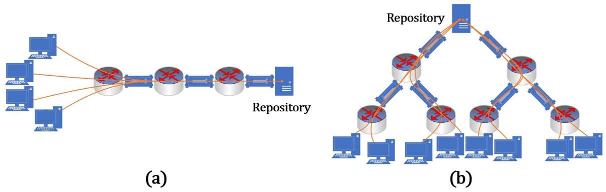


Fig. 2. Network topologies: line (a) and binary tree (b)

As approximated by Che [2] we know the request process in a single cache with LRU replacement strategy. The process by which a request arrives at a cache node is a Poisson process, while the process by which a content request i arrives at a parent cache node is not a simple Poisson process, but rather a switch-modulated Poisson process. Requests for this content are forwarded to the parent cache node if it does not exist (on state); requests for content i cannot reach the parent cache when the content is present in the edge cache (off state) [6].

A request for content can reach the parent cache at time (t-τ_2 , t-τ_1) if τ_2 >τ_1 is satisfied. The interval reaches the parent cache node at time t, when content i is requested again, there is no copy of that content in the edge cache, and forwarding the request to the parent cache, thus hitting in the parent cache. During this time interval, the content request process in the parent cache is not a Poisson process, but we can approximate it using a Poisson process with rate λ_2:

$$\lambda_2(i) = \mu_1(i) = \lambda(i)e^{\quad \lambda(i)\tau_1} \tag{10}$$

$$\sum_{i=1}^{N} P_{in}(i) = \sum_{i=1}^{N}(1 - e^{-\lambda_2(i)\tau_2}) = C_2 \tag{11}$$

$$hp_2 = \sum_{i=1}^{N} q_2(i)P_{hit}(i) = \sum_{i=1}^{N} q_2(i)\left(1 - e^{-\lambda_2(i)(\tau_2 - \tau_1)}\right) \tag{12}$$

We can continue to recursively compute the popularity distribution of the next layer, solve for the characteristic time of the next cache node, and then calculate the miss probability of it:

$$q_l(i) = \frac{\sum_{k=1}^{K} mp_{l-1,k}(i)q_{l-1}(i)}{\sum_{n=1}^{N}\sum_{k=1}^{K} mp_{l-1,k}(i)q_{l-1}(i)} \tag{13}$$

$$hp_l = 1 - \frac{\sum_{i=1}^{N}\lambda_i\prod_{j=1}^{l} mp_j(i)}{\sum_{i=1}^{N}\lambda_i\prod_{j=1}^{l-1} mp_j(i)} = 1 - \sum_{i=1}^{N} q_l(i)mp_l(i) \tag{14}$$

For example, the total hit probability of a layer 2 hit for a linear or symmetric tree topology can be written in the formula:

$$\begin{aligned} hp_2 &= 1 - \frac{\sum_{i=1}^{N}\lambda(i)e^{-\lambda(i)\tau_1}e^{-\lambda(i)e^{-\lambda(i)\tau_1}(\tau_2-\tau_1)}}{\sum_{i=1}^{N}\lambda(i)e^{-\lambda(i)\tau_1}} \\ &= 1 - \sum_{i=1}^{N} q_l(i)e^{-\lambda(i)e^{-\lambda(i)\tau_1}(\tau_2-\tau_1)} \end{aligned} \tag{15}$$

Next, let's consider the case of asymmetric tree topology, assuming that there are two edge nodes with the same request rate λ but different cache sizes. From Eq.(1) we can calculate that the characteristic times τ_{11} and τ_{12} of the two edge cache nodes are also different. The hit probability computed from (2) is also different. Here is the process of calculating the characteristic time and the hit probability of the parent cache node of the asymmetric tree topology:

$$\sum_{i=1}^{N} 1 - e^{-\lambda_2(i)\tau_2} = \sum_{i=1}^{N} 1 - e^{-\lambda(i)\frac{e^{-\lambda(i)\tau_{11}}+e^{-\lambda(i)\tau_{12}}}{2}\tau_2} = C_2 \tag{16}$$

$$p_2 = 1 - \frac{\sum_{i=1}^{N}\lambda(i)\,(A+B)}{\sum_{i=1}^{N}\lambda(i)e^{-\lambda(i)\tau_{11}} + \lambda(i)e^{-\lambda(i)\tau_{12}}} \tag{17}$$

$$A = e^{-\lambda(i)\tau_{11}}e^{-\lambda(i)e^{-\lambda(i)\tau_{11}}(\tau_2-\tau_{11})}$$
$$B = e^{-\lambda(i)\tau_{12}}e^{-\lambda(i)e^{-\lambda(i)\tau_{12}}(\tau_2-\tau_{12})}$$

IV. PROBLEM SOLVING

A. Resource Estimation

In the practical application of ICN networks, it also needs to configure network parameters to meet the performance metrics. The most intuitive is to determine the cache size and bandwidth. We assume that the performance metric is the hit probability of each node (other performance metrics such as the request response time can also be derived from the hit probability, which is described in III-A).

The characteristic time τ is calculated by (18) as follows:

$$1 - \sum_{i=1}^{N} q(i)e^{-\lambda(i)\tau} = hp \tag{18}$$

then the cache size is calculated by (19):

$$C = \sum_{i=1}^{N} 1 - e^{-\lambda(i)\tau} \tag{19}$$

Similarly, after calculating the feature time τ_1 for an edge node using (18), the parent node popularity distribution q_2 (i) given by (13), the parent node content i request rate λ_2 (i) given by (10), use (20) to calculate the parent node's characteristic time τ_2:

$$1 - \sum_{i=1}^{N} q_2(i)e^{-\lambda_2(i)(\tau_2-\tau_1)} = hp_2 \tag{20}$$

After computing τ_2, then substitute it into (19) to compute the parent cache size. The bandwidth size estimate:

$$bandwidth = \lambda \cdot \mathrm{mp} \tag{21}$$

B. Parameter Optimization

Taking the single-node cache as an example, if the cache is enlarged, we know from the Che approximation that the characteristic time of the node will also be enlarged, thus increasing the hit probability of the cached node and improving the filtering performance of the node, so that the number of requests forwarded out by the node will be reduced and the required bandwidth size will be smaller. So in terms of total network cost, bandwidth cost and cache cost are negatively correlated. It is possible that the cost remains essentially the same but the parameters change in the direction of better performance metrics. Parameter optimization is theoretically feasible.

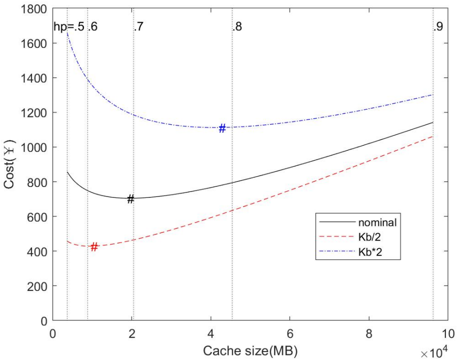


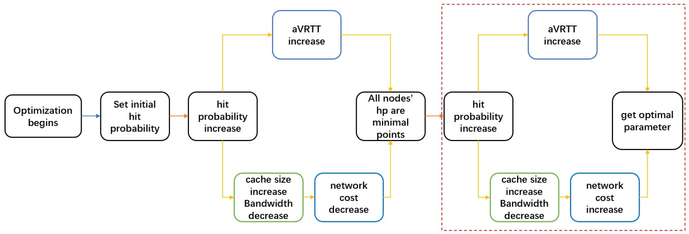
Fig. 3. Total network cost - cache size, for different k_b parameters.

With other conditions such as request rate λ, Zipf parameter α, and a number of contents determined, we can calculate the cache size and bandwidth from the hit probability. And from the cost formula (9) we can calculate the operating cost size. The total cost can be considered as a function with either the cache size or the hit probability as parameters. By calculating, we find that there is a minimal value of the total cost of the network as it varies with the cache size. As shown in Figure 3, the position of the minimal value point also changes when the cost formula takes different values for k_b and k_m.

From Figure 3 we can see when k_b increases, the bandwidth cost of the cost equation is larger, the cache size increases, the bandwidth decreases, and thus the cost is lower; when k_b decreases, the cache cost of the cost equation is larger, the cost is lower by increasing the bandwidth and decreasing the cache. The process we want to implement is to input the total cost constraint, the bandwidth cost k_b and the caching cost k_m, set parameters such as the Zipf parameter, request strength, number of content, content item size, and to output the optimal node parameter configuration.

First, we set the same initial small hit probability. Next we can estimate the characteristic time and cache size according to (18)(19)(20) given in IV-A, noting that the order of estimation is from the edge cache node to the parent cache node. Then calculate the bandwidth and the network cost at the current parameter settings according to the cost formula (9). The initial hit probability is set small so that we can directly increase the hit probability to reach the smallest point of the cost-cache size function.

When all cache nodes reach the smallest value point of the cost-cache size function, the cost of the entire network reaches a theoretical minimum. If it is less than the given cost limit, then subsequent optimizations can continue. In other words, a portion of the cost is sacrificed in exchange for the user's performance experience so that the aVRTT continues to be reduced. Select the node with the highest increase in performance metrics at the same cost increment, and continue to increase hp until the cost exceeds the preset. The whole parameter optimization process is shown in Figure 4.



Each step selects the highest R value for iteration

Fig. 4. Parameter optimization process

V. EVALUATION

In this section, we evaluate the accuracy of our models and the effectiveness of parameter optimization by comparing them against simulations. Simulation environment: Ubuntu 18.04. and 2.7 version ndnSIM. Meta-caching algorithm sets as leave copy everywhere(LCE), replacement algorithm is the Latest Recently Used (LRU) policy, and forwarding policy is Shortest Path Routing (SPR).

A. Network of Caches

First, we evaluate the improved cache network model against simulations. The model is validated by simulation with an error of about 5%. The result is shown in Figure 5-8. In all experiments of cache network, a number of content N = 20000, request rate of edge node λ = 20. In Figure 5, Zipf parameter α = 1.0, we study the effect of parent cache node size on its hit probability, as well as scenarios with different edge cache node sizes. Evidently, the larger the edge cache, the smaller the hit probability of the parent cache node, because the edge cache nodes have a greater filtering effect. In addition, we also compare the computational results of Eq.(4). In Figure 6, Zipf parameter α = 1.0, the hit probability of the entire cache network is calculated for different parent cache sizes. There is excellent agreement between analysis and simulation.

In Figure 7, Zipf parameter = 1.0, we calculate the hit probability with different cache size and different Zipf parameters. The higher the Zipf parameter, the higher the hit probability, and the hit probability grows sub-linearly with the cache size. In Figure 8, we study the influence of cache size of edge node on hit probability of parent node in asymmetric topology, α = 1.0, C of parent node = 800. While the hit probability of the parent node decreases as the cache size of an edge node increases, which is due to the fact that more popular content moves down and is satisfied at the edge, the other leaf node is unaffected.

B. Process of Optimization

Next, we perform simulation to verify the parameter optimization idea. Optimize the parameters of a two-layer, asymmetric binary tree topology with different request rate for different leaf nodes. Ndnsim simulation verifies whether the performance metrics of the network are optimized with the iterations, as shown in Figure 9. N = 20000, λ_{11} = 20, λ_{11} = 10, zipf parameter α = 1.0, content size = 10MB, cost of traffic k_b = 0.1U/MB, cost of memory k_m = 0.001U/MB, propagation delay t_p = 0.5ms, transmission delay t_{tr} = 50ms, monthly operating cost limits = 22U.

In Figure 9, sections a-b of the curve are the simulation results of the leaf node 11 (with higher request strength) in the phase of increasing hit probability. The b-c segment of the curve is the stage where the probability of hitting leaf node 11 decreases. It can be seen that the performance indicator VRTT increases slightly at this time, but the total cost of the network decreases at this time. Then segments c-d and d-e of the curve respectively simulate the increase and decrease in the hit probability of leaf node 12 (with less request intensity). The cost trends of its performance metrics and total network are generally consistent with leaf node 11.

The e-f segment of the curve is a simulation of the process of adjusting the hit probability of the parent node. The f-g segment of the curve achieves an improvement in performance metrics at some cost. The entire simulation results are basically

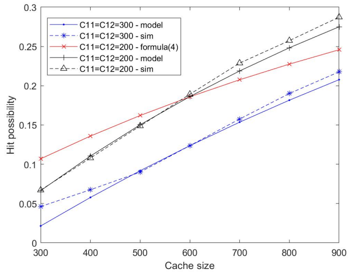


Fig. 5. Hit probability - cache size of parent node C_2, symmetric binary tree topology

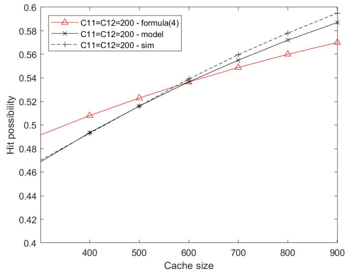


Fig. 6. Total hit probability - cache size of parent node C_2, symmetric binary tree topology

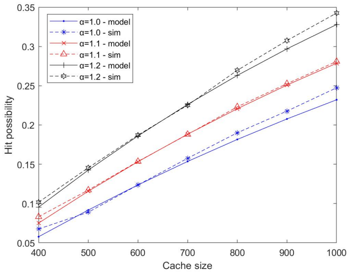


Fig. 7. Hit probability - cache size of parent node C_2, for different zipf parameter, symmetric binary tree topology

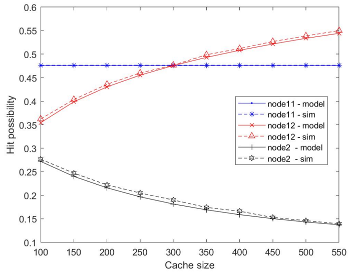


Fig. 8. Hit probability - cache size of edge node C_{12}, asymmetric binomial tree topology

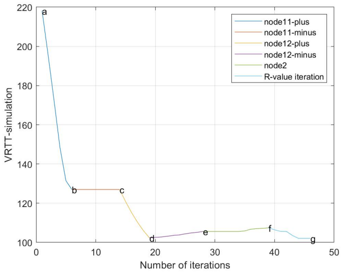


Fig. 9. Optimization based on the improved model - Simulation

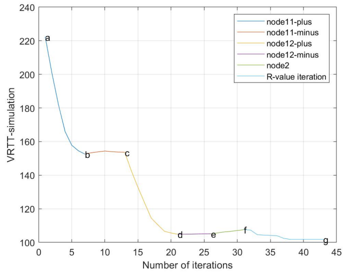


Fig. 10. Optimization based on unimproved model - Simulation

consistent with the model. The optimization process based on the unimproved model is shown in Figure 10. Small errors in the model are constantly magnified during the planning process, especially when making minor adjustments, and then affect the final planning results.

VI. CONCLUSION

For operators, how to lower the TCO(Total Cost of Ownership) and how to ensure the network service quality are the focal points of attention, the importance of network planning and design is becoming more prominent. We model the ICN network planning problem, improve the accuracy of the tree topology network model based on the Che approximation, and obtain the solution to the planning problem. We also evaluate the accuracy of our models and the effectiveness of parameter optimization by comparing them against simulations.

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