A Comparative Analysis of Content Delivery Capability for Collaborative Dual-Architecture Network

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Abstract. In order to deliver Internet content to people of the world for achieving the vision of "The Internet is for everyone", our group pioneered a collaborative dual-architecture network (DAN). For quantitative analysis of DAN's content delivery capability, in this paper we firstly propose a unified comparative model, in which network performance and user utility are taken into account. Then, by applying the model we conduct direct and indirect comparative analysis in detail. Numerical results shed light on that DAN outperforms TCP/IP, NDN (named data networking) and BSN (broadcast-storage network) in terms of delivery capability. Given this, we argue that DAN is favourable for content delivery.

Keywords: Dual-architecture · Content delivery
Comparative analysis · Network performance · User utility

1 Introduction

Along with the development of mobile networks and the widespread of intelligent terminals, urban residents can not only enjoy numerous contents through access to the Internet but also generate contents by themselves. As a significant driver the content is prompting the Internet evolving from an initial communication oriented network to content oriented one [1]. However, according to the latest survey released by Internet Society, currently, approximately 60 percent of the earth's population fails to access the Internet due to the factors of demographic, geographic and economic. Therefore, it's imperative to delivery Internet content to people of the world, especially for whom in the area with limited Internet infrastructure support, to eliminate the digital divide and achieve the vision of "The Internet is for everyone" envisaged by Vint Cerf.

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By its nature, the packet-oriented TCP/IP fails to be an ideal architecture for content delivery. To this end, there exist two types of approaches: (1) the dirty slate: constructing an overlay network above the packet-oriented network, e.g. content delivery network (CDN); (2) the clean slate: constructing a brand-new content-oriented architecture from scratch (e.g. NDN, content-centric networking (CCN)). Although the benefits of incremental deployment make the former become the overwhelming content delivery architecture currently, it's difficult for the parasitic architecture to deliver content in area with limited infrastructure. As to the latter, although the delivery efficiency could be significantly increased by in-network caching, the cost of reconstructing hinders the pace of deployment.

To solve the issue, our group led by Prof. Youping Li, the academician of Chinese Academy of Engineering, pioneered the big picture of DAN [2], which is composed of primary architecture (refers to TCP/IP) and secondary architecture (refers to BSN [3]), as shown in Fig. 1. From perspective of architecture, the relationship between the two architectures is symbiotic and complementary, which breaks the dependency of the overlay content-oriented network on TCP/IP. Furthermore, the secondary architecture, on one hand, adopts additional broadcasting transmission channels, such as digital cable, terrestrial, satellite and mobile broadcasting, to deliver content with less hop counts and more broad transmission range. The edge box, such as router/switch, set-top box, and Internet box, on the other hand, is used to store broadcasted contents locally in advance for reducing response delay of user's content request.

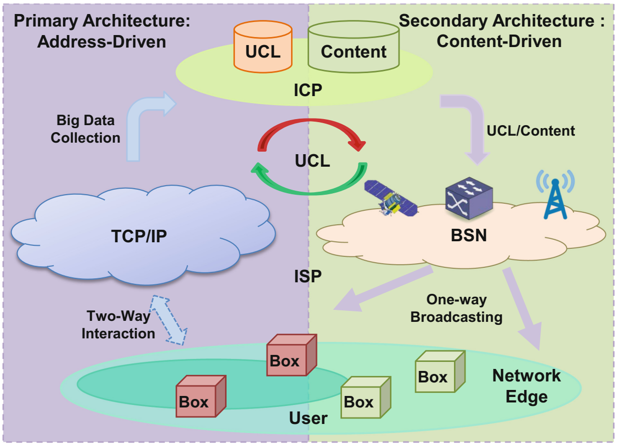

Fig. 1. The big picture of DAN

As an operational architecture involving stakeholders' interest (e.g. Internet Service Provider (ISP), Internet content provider (ICP) and user), even if DAN embracing many outstanding features especially in terms of architecture, in order to provide guidance for stakeholders' investment decision it's necessary to compare and analyse content delivery capability of DAN with the other architectures, such as TCP/IP and NDN. Thus, how to quantitatively analyse the capability is an urgent problem to be solved. Despite its importance, to the best of our knowledge, as of yet, no solutions have been presented. This paper addresses the problem for the first time and makes the following key contributions:

- *We proposed a unified comparative model of content delivery capability for network architecture from a high-level perspective, in which network performance and user utility are taken into account.*
- *We utilized the proposed model to quantitatively compare and analyse content delivery capability of DAN with TCP/IP, NDN and BSN to shed light on its superiority.*

The remainder of this paper is organized as follows: In Sect. 2 we introduce the related work. In Sect. 3 we present a multi-dimension methodology of comparing content delivery capability for architecture. In Sect. 4 we present a unified comparative model of the delivery capability, and followed by Sect. 5, we conduct direct comparative analysis on DAN with TCP/IP and NDN, and indirect comparative analysis on DAN with TCP/IP and BSN. Finally, concluding remarks are offered in Sect. 6.

2 Related Work

The related comparative work in area of network architecture can be divided into two major categories: qualitative and quantitative. For the qualitative comparative, the authors in [4,5] conducted comparing on the dirty slate architecture with the clean slate one, and the work [6] qualitatively analysed the evolution relationship between Internet architectural and biological. Although the qualitative studies can clearly illustrate the pros and cons of various architectures, the lack of rigorous mathematical proof makes those results difficult for stakeholders to make investment decision. For the quantitative comparative, the vast majority of work concentrate the comparative analysis on architecture in single aspect, such as transmission performance [7], scalability [8], deployment [9], evolution [10], and adaptability [11]. However, as of yet, no quantitative comparative analysis work on the content delivery capability for network architecture has been found.

In the closely related work, the authors in [12] proposed the 2ACT evaluation model. Our work is different in that their comparative model is used to compare application adaptation capability and takes network performance and economic factor into consideration while we respectively compare content delivery capability from bottom-up and top-down dimensions. Furthermore, although the authors in [13] adopted user utility to model convergence process of telecommunication network, TV broadcasting network and Internet, our work is different in that we conduct not only indirect comparison of content delivery capability by means of user utility but also direct comparison by means of network performance. Integrating advantages of the two models, we proposed a unified comparative model of content delivery capability for network architecture.

3 Methodology

In this section, we will present multi-dimension methodology of comparative analysis of content delivery capability for network architecture from a high-level perspective.

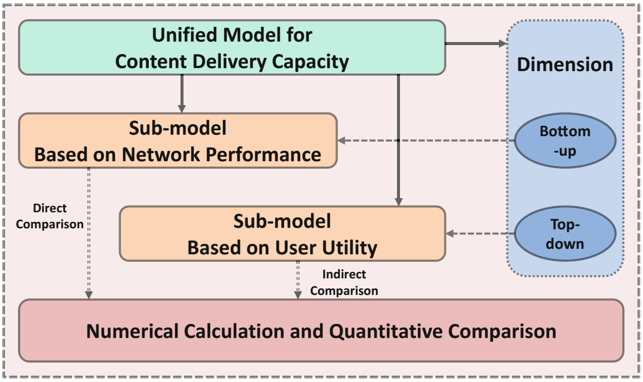

Fig. 2. A methodology of comparative study on content delivery capability

As user is ultimate consumer of content services it's more appropriate to evaluate content delivery capability from user's point of view. Therefore, we propose a methodology of comparative analysis as shown in Fig. 2. Above all, a unified comparative model including two dimensions, as shown in Fig. 2, needs to be constructed. The bottom-up dimension refers to directly compare according to network performance, while the top-down dimension refers to indirectly compare according to user utility. Then, based on the model various numerical calculation and quantitative comparison need to be conducted. Finally, the content delivery capability of architecture can be clearly obtained.

- *Bottom-Up Dimension*
  Starting from architecture itself, for user it's quality of content service that could be considered as the equivalent to content delivery capability. While the quality depends on network performance of architecture, for example, naming method, routing protocol and transmission mechanism. Therefore, the comparative model based on network performance is key to directly analyse.
- *Top-Down Dimension*
  Starting from external of architecture, for user utility generated by consumption of content service is capable of indirectly reflecting content delivery capability while the utility function depends on various factors. Therefore, the comparative model based on user utility is key to indirectly analyse.

4 Unified Comparative Analysis Model of Content Delivery Capability

In this section, we will detail a unified comparative analysis model. According to the methodology above it consists of sub-model based on network performance and sub-model based on user utility, as shown in Fig. 3.

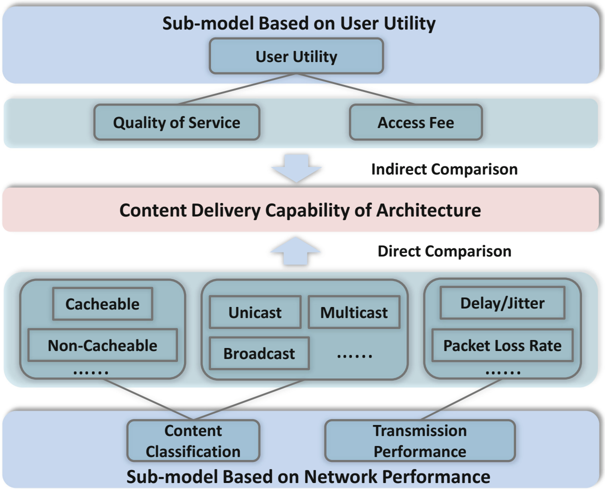

Fig. 3. A unified comparative analysis model of content delivery capability

In sub-model based on network performance, we model network performance as the product of content classification and transmission performance. As to content classification, there exist numerous content classifications, for instance, content can be divided into cacheable and non-cacheable on basis of reusability. As to transmission performance, it includes but not limited to the current network performance metrics, such as delay/jitter, error rate and loss rate.

In sub-model based on user utility, we take advantage of quality of content service and content access fee as primary parameters of utility function. The quality can reflect users' gain and the fee can reflect users' cost.

4.1 Sub-model Based on Network Performance

We denote A as an architecture to be compared and model the sub-model based on network performance as:

$$CDC_A = \frac{1}{m}\sum_{i=1}^{m}\sum_{j=1}^{n} p_{ij} T_{cont}(Perf)_{ij,A} \qquad s.t. \sum_{j=1}^{n} p_{ij} = 1 \tag{1}$$

where m is the number of content classifications and n is the number of content types in particular classification. T_{cont} is the total amount of the content in the network and p_{ij} is the proportion of the content of the classification i and the type j. $(Perf)_{ij,A}$ is the transmission performance of the classification i and the type j in the architecture A, which is expressed as performance function with specific metric parameters.

The selection of classification method and the design of performance function can be customized by model user according to different requirements. Since content forwarding hop count can reflect transmission performance to some extent, we utilize the product of average content forwarding hop counts $H_{ij,A}$ and transmission performance in each hop to represent the performance denoted as $(HPerf)_{ij,A}$, and then the sub-model can be converted as:

$$CDC_A = \frac{1}{m}\sum_{i=1}^{m}\sum_{j=1}^{n} p_{ij}T_{cont}(HPerf)_{ij,A}H_{ij,A} \tag{2}$$

By Formula 2 we can obtain that the smaller the value of CDC_A is the better the delivery capability of the architecture will be. Given p_{ij}, $H_{ij,A}$ and $(HPerf)_{ij,A}$ under a particular classification, the value of CDC_A for an architecture can be calculated to compare with other architectures.

4.2 Sub-model Based on User Utility

Supposing that user is capable of selecting TCP/IP or BSN to access Internet content, we use $n \in \{1, 2\}$ respectively to denote the two architectures, and use the status $s \in \{1, 2, 3\}$ respectively to denote the user's decision, that is one of architectures and both of them (that is DAN). The parameter $k_{s,n} = 1$ indicates whether to select the architecture n at the particular status s or not. Subsequently, we suppose the total number of user is T and denote P_s as the proportion of the number in the status s. Due to $\sum_{s=1}^{3} P_s = 1$, the number of user who select the architecture n is $T_n = \sum_{s=1}^{3} k_{s,n}P_sT$. Then we formulate the sub-model based on user utility under the status s as:

$$CDC_s = U_s = \alpha\sum_{t=1}^{3}\max_{1\le n\le 2} q_{n,t}k_{s,n}R_t - \beta\sum_{n=1}^{2} k_{s,n}f_nT_n/T \tag{3}$$

The first half of Formula (3) indicates the gain user obtain through consuming content services while the second half represents the cost user spend, where t is content type provided by an architecture. We use $t \in \{1, 2, 3\}$ respectively represent non-sharing (such as voice, instant message, etc.), real-time sharing (such as live television, etc.) and non-realtime sharing (such as a document, image, etc.). The parameter R_t denotes user demand for the content of the type t, which is used for representing proportion of the content in the architecture n in the paper. The parameter $q_{n,t}$ is quality of content service supplied by the architecture n while f_n is access fee which is paid for using the architecture n

by user. In addition, the impact factor α indicating user's personal view to the quality, which reflects the differences among user in various social classes, while the impact factor β is used to balance the impact on user utility generated by user's benefit and expense.

By Formula 3 we can obtain that the bigger the value of CDC_s is the better the delivery capability of an architecture will be. Given specific parameter value, once the user utility from an architecture is calculated based on the sub-model, the value of CDC_s will be obtained.

5 Numerical Calculation and Comparative Analysis

In this section, we will conduct numerical calculation and comparative analysis of content delivery capability in direct and indirect ways by using the proposed unified comparative analysis model.

5.1 Direct Analysis

Because one of the biggest difference among TCP/IP, NDN and DAN is in-network caching, therefore we categorize the content into non-cacheable and cacheable. For example, real-time content, such as TV live and instance message, belongs to the non-cacheable type while non-realtime content such as video on demand is cacheable. Without loss of generality, we set average hop count of the non-cacheable in TCP/IP as $H = 16$. According to [11], hop count of the cacheable in NDN is $H^{'} = 7$. In DAN, due to user's request hit in local on the benefit of storing content into edge devices in advance through broadcast channel we set hop count of the cacheable in DAN as $H^{'} = 1$. Supposing that a piece of content is bigger than an IP packet, it's obvious that content transmission delay in a hop is higher than IP packet. Therefore we set forwarding performance in a hop in content-oriented network (refers to NDN and DAN) as r times higher than that in TCP/IP. Then, we denote the performance in a hop in TCP/IP as $(HPerf)_{TCP/IP}$ and the performance in content-oriented network is $r(HPerf)_{TCP/IP}$, $r \geq 1$. In addition, the proportion of the non-cacheable content is p_1 and the cacheable content is $p_2(p_1 + p_2 = 1)$. Hence, according to Formula 2 and the average hop count, we can get the value of content delivery capability in the three architectures as follows:

$$\begin{cases} CDC_{TCP/IP} = 16(HPerf)_{TCP/IP} \\ CDC_{NDN} = 7r(HPerf)_{TCP/IP} \\ CDC_{DAN} = (16P_1 + rp_2)(HPerf)_{TCP/IP} \end{cases} \quad (4)$$

As shown in Fig. 4, proportion of cacheable content doesn't affect the delivery capability of TCP/IP, as to DAN and NDN, the capability is bound to increase with the increase of the proportion. Comparing with NDN, the capability of DAN possesses a clear advantage no matter how the value of r changes and the advantage is inclined to increasing with the rising of the proportion of cacheable content. However, comparing with TCP/IP, DAN also possesses a clear advantage when $r = 1$, while with the rising of r, it will exceed TCP/IP when the proportion of cacheable content increases to a certain threshold. And according to the fact that the threshold in DAN is lower than that in NDN, it's proved that DAN can obtain the higher delivery capability with less content cache.

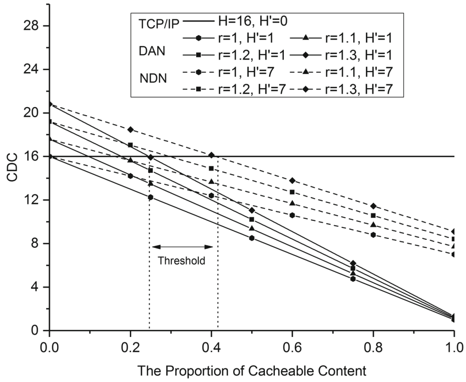

Fig. 4. The content delivery capability under the different architectures

5.2 Indirect Analysis

The quality of non-sharing content in TCP/IP, which is initially designed for end-to-end communication, is destined to surpass BSN. On the benefits of broadcasting mechanism, however, BSN is far ahead of TCP/IP in terms of content delivery. Therefore, we set the quality relationship among various content types as shown in Table 1.

Table 1. The quality relationship among various content types

Content type (t)	TCP/IP ($n = 1$) BSN ($n = 2$)
Non-sharing ($t = 1$)	$q_{1,1} \geq q_{2,1}$
Realtime sharing ($t = 2$)	$q_{1,2} \leq q_{2,2}$
Non-realtime sharing ($t = 3$)	$q_{1,3} \leq q_{2,3}$

In order to eliminate the difference between multi-dimensional parameters in the sub-model for making the value of Formula 3 comparable, we use the decimal scaling normalized method to standardize the specific values as follows. Quality of content is set as $q_{1,1} : q_{1,2} : q_{1,3} = 1 : 0.6 : 0.7$, $q_{2,1} : q_{2,2} : q_{2,3} = 0.2 : 1 : 0.9$. User demand is set as $R_1 : R_2 : R_3 = 0.2 : 0.3 : 0.5$ on basis of proportion of content types in network. Content access fee f_n is set as $f_1 : f_2 = 0.7 : 0.3$

according to the costs of architecture operation, such as equipment, maintenance and manpower. Supposing that the initial user follows a uniform distribution, we set $T_n/T = 1$ when the status is $s = 1$ and $s = 2$ and we set $T_n/T = 0.5$ when the status is $s = 3$.

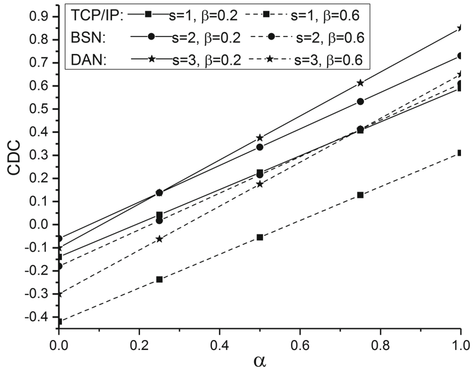

Fig. 5. The content delivery capability under different user evaluation factors and economic factors

As shown in Fig. 5, the delivery capability both BSN and DAN is better than TCP/IP no matter how the user evaluation factor α changes. Due to the higher the access fee on the ground of the costs in operation, the delivery capability of BSN is better than DAN in the initial stage. However, with the rising of the number of user, DAN is bound to exceed BSN as α increases to some certain threshold. Furthermore, although the delivery capability of the three architectures will decrease with the increase of economic factor β, DAN is also better than BSN and TCP/IP.

6 Conclusion

In this paper, we focused on the comparative analysis of content delivery capability of DAN with other architectures. Firstly, we proposed a unified comparative analysis model from a high-level view, in which network performance and user utility are taken into account. Further, we utilized the model to conduct direct comparative analysis of the delivery capability of DAN with TCP/IP and NDN, and the numerical results showed that DAN possesses a clear advantage that it will further increase with the rising of the proportion of cacheable content. Then we utilized the model to conduct indirect comparative analysis of the delivery capability of DAN with TCP/IP and BSN, and the numerical results revealed that DAN also outperforms them. Briefly, DAN is favourable for being an ideal content delivery architecture than other architectures.

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