

# A Fairness Analysis of Content Centric Networks

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**Abstract**—In recent years the new vision of data-centric networks has emerged as a natural way to satisfy user needs in the Future Internet. It is based on novel architectures oriented towards data sharing and delivering as opposite to classic host-to-host communications. Among several proposals, *Content Centric Networking* has been conceived as a very promising solution by the Palo Alto Research Center team. It can be gradually deployed over current IP networks and solves different problems, as NAT Traversal, depletion of IP addresses, security, mobility, and multicast communications. In this work an analytical framework for investigating properties of Content Centric Network is proposed, with a particular focus on fairness in cache usage. It captures the distribution of content replicas among nodes of the network by taking into account contents availability, data popularity, topology information, and cache size. Preliminary results, validated using numerical simulations, shed some light on the underlying fairness of a Content Centric Network, thus helping future developments and upgrades on the current architecture.

**Index Terms**—Data centric networks, CCN, theoretical model.

## I. INTRODUCTION

The last decade has been characterized by a gradual and significant change in the way Internet is used. People desire an efficient and secure access to collections of contents and services, regardless of the host that actually provides them. In other words, consumers are interested in “what” Internet offers, whereas networking technology is still based on “where” contents are. This mismatch between network technology and its use causes complexity for application and inefficiency in network use [1].

As a consequence, in recent years, there have been several proposals having as target a new way to think network architectures. These proposals are based on a “data-centric” approach, in which “what” is the main focus, whereas “where” becomes less important. According to this new paradigm, all contents should be identified by a unique name, allowing users to retrieve information without having any awareness about the physical location of servers (e.g., IP address). Furthermore, in this new approach, each content becomes an entity that includes all the mechanisms useful to verify its integrity and validity.

Main advantages of data-centric networks are: (i) traffic and congestion decrease; (ii) also scenarios characterized by limited connectivity are supported; (iii) robustness to attacks to content servers; (iv) native data security (given that each content can be authenticated by digital signatures and protected by encryption). There are two different approaches to build a data-centric infrastructure. With the “clean-state” one,

the entire architecture is fully modified and the TCP/IP stack is almost substituted by new paradigms. Examples of this approach are the PSIRP (Publish Subscribe Internet Routing Paradigm) architecture [2], the 4WARD NetInf project [3], and the Cache-and-Forward Network Architecture [4].

The second approach, instead, is based on “overlay networks” and includes all the proposals based on the IP protocol, such as Data-Oriented Network Architecture [5] and Content-Centric Networking (CCN) [1].

We focus herein on CCN because it can greatly improve network performance by solving many problems of the existing protocols, it is fully compliant with existing infrastructures (hardware and protocols), and it enables secure data sharing applications [6]. Further, it eases mobility and wireless access, and it can be particularly beneficial in an ad-hoc networking environments [7].

Due to the relevance of the CCN approach, several models have been proposed to catch its main properties. In [8] an analytical model, based on continuous time Markov-chains, is derived to determine the percentage of time a content is cached in any node along the path to the server, while in [9], a closed form expression for average content delivery time is presented. Carofiglio et al., in [10], instead, focus on a set of different storage management techniques to differentiate the QoE perceived by users.

To contribute to this hot research topic, in this work, we propose closed form expressions that model CCN fairness in cache usage, taking into account the network size (expressed in terms of number of nodes), the number of contents, the cache size, the average path length in an overlay, and the content popularity. In particular, we found that the rise of the number of the cached copies of a content, with respect to its popularity, is linear at low popularity values, whereas it becomes more than linear at intermediate popularities, and, finally it approaches a less than linear trend. These results have been also validated using computer simulations.

The rest of the paper is organized as follows. In Sec. II, the CCN architecture is briefly described. In Sec. III, a novel theoretical model for CCN is proposed. In Sec. IV, a validation of theoretical results is performed using computer simulations. Finally, in Sec. V, we draw conclusions and forecast future research.

## II. BASIC BACKGROUND ON CCN

The core of the CCN vision is to retrieve contents by their names instead of by their network addresses. CCN is a part of a larger project called *Named Data Networking* [11], which is

one of the four proposals for the “Future Internet Architecture” initiative, proposed by the National Science Foundation (NSF).

To explain the main features of this new architecture, we compare the IP and CCN protocol stacks in figure 1.

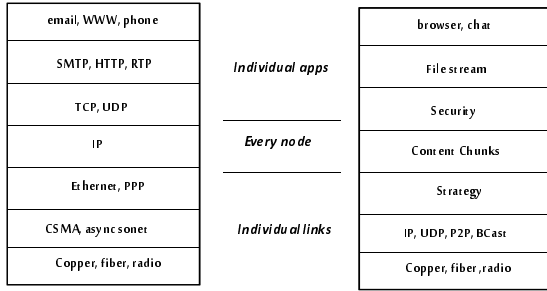


Fig. 1. IP and CCN protocol stacks.

The main difference is in the network layer. In fact, CCN shifts the main focus from IP addresses to content names, and introduces the *strategy* and *security* layers which deal with data dissemination and security, respectively. In this way, IP networks become a basic technology to enable internetworking whereas contents are at the center of the system.

There are only two type of messages exchanged between network nodes: *Interest* and *Data*. A consumer asks for a content by diffusing an *Interest* packet to all the potential source of that content in the network. Any node receiving the *Interest* and having the required data replies with a *Data* packet. Other nodes just forward the *Interest* message on the overlay network. Distributed caching is also adopted to improve the efficiency of the system. In fact, each node is equipped with a Content Store (i.e., a cache memory), that can implement different replacement policies. e.g, Least Recently Used (LRU) or Least Frequently Used (LFU)) [12].

All network operations are driven by content names. Hence, a hierarchical structure of *names* is useful to manage large collections of data. For this reason, a CCN name is formed by several components, each one a number of arbitrary octets (optionally encrypted) long. The names of all possible contents form a *name tree* and a *name prefix* identifies a sub-tree.

An *Interest* can specify the content required with the full name of the *Data*, when it is known, or with its prefix. In the latter case, specifying the prefix it is possible to access to the entire collections of data that are in the sub-tree identified by that prefix.

### III. THE MODEL

In this section, we describe the diffusion process of a number of contents within the overlay network by using a discrete-time model. To simplify the analysis, we split the time axis in slots. During the  $k$ -th slot all requests made in the previous  $(k-1)$ -th slot are served. Further, we focus on equally sized contents to evaluate the fairness in resource sharing with respect only to content popularity <sup>1</sup>.

We will use the following basic notation:

- $S$ : total number of nodes in the overlay network.
- $M$ : total number of contents in the overlay network.
- $H$ : average path length (hops).
- $B$ : maximum number of contents that a node can store in the *Content Store* (i.e., the cache size).
- $n_i(k)$ : total number of nodes with a copy of the  $i$ -th content during the  $k$ -th slot.
- $\pi_i$ : popularity of content  $i$ ; it is the probability that a node issues a request for the  $i$ -th content during a slot.
- $p_i(k) = (S - n_i(k))/S$ : probability that a node does not store a copy of the  $i$ -th content in the  $k$ -th slot.
- $A = B \cdot S - M$ : total cache space available for new copies.

*Remark 1:* By analyzing the physical characteristics of our system, it is possible to show that the following constraints hold:

$$1 \leq n_i(k) \leq S \quad (1)$$

$$B \ll M \quad (2)$$

In fact, these constraints express that each node can store up to one copy of the same content - eq. (1) - and that the cache size  $B$  cannot store all the  $M$  available contents - eq. (2). Furthermore, eq. (1) also says that at least one copy of each content is stored within the network (i.e., the seed copy). As a consequence, the total cache space available for new copies is  $A$ , i.e., the total cache space  $B \cdot S$  minus one seed for each content.

During the  $k$ -th timeslot, the average number of requests for the  $i$ -th content is equal to  $\pi_i[S - n_i(k)]$ , i.e., the number of nodes that do not store yet a copy for that content,  $[S - n_i(k)]$ , times the content popularity  $\pi_i$ . Each one of these requests will trigger a number of replies equal to  $n_i(k)$ . Each reply will go through a path with  $H$  hops length; so that, no more than  $H \cdot n_i(k)$  new nodes will cache the content  $i$  during the  $k$ -th slot.

Further, we have to consider that the probability that a node does not store a copy of the  $i$ -th content yet is  $p_i(k) = (S - n_i(k))/S$ . As a consequence, the average number of new copies of the  $i$ -th content issued during the  $k$ -th slot will be:

$$D_i(k) = \pi_i[S - n_i(k)] \cdot H \cdot n_i(k) \cdot p_i(k) \quad (3)$$

Let  $D_T(k) = \sum_{i=1}^M D_i(k)$  be the total number of maximum new copies. We have to consider two possible scenarios: in the first one  $D_T(k) > A$ , i.e., the overall cache availability is not enough for the  $D_T(k)$  copies. In this case, all existing content copies will be replaced by new ones.

In the second scenario, instead,  $D_T(k) \leq A$ , i.e., the overall available cache size  $A$  can accommodate new content copies at the expense of a quota of the existing ones.

Hence, we can describe the system dynamics as follows:

$$\mathbf{n}(k+1) = \mathbf{f}[\mathbf{n}(k)] \quad (4)$$

where  $\mathbf{n}(k) = [n_1(k), n_2(k), \dots, n_M(k)]$  and  $\mathbf{f}[\mathbf{n}(k)] = \{f_1[\mathbf{n}(k)], f_2[\mathbf{n}(k)], \dots, f_M[\mathbf{n}(k)]\}$ .

<sup>1</sup>Future research will cover also the case of contents having different sizes.

Furthermore, each  $f_i[\mathbf{n}(k)]$  can be expressed as:

$$f_i[\mathbf{n}(k)] = \begin{cases} 1 + A \cdot \frac{D_i(k)}{D_T(k)}, & \text{if } D_T(k) > A \\ 1 + D_i(k) + \frac{n_i(k)}{B \cdot S} [A - D_T(k)], & \text{otherwise.} \end{cases} \quad (5)$$

In fact, when  $D_T(k) > A$ , the total number of copies issued in the  $k$ -the slot cannot be accommodated in the caches. As a consequence, only a quota of them will be stored for each content, which is proportional to the ratio  $D_i(k)/D_T(k)$ . On the opposite, when  $D_T(k) \leq A$ , for each content, the new  $D_i(k)$  copies can be fully cached, and a quota of past copies can be still remain stored, which is equal to  $\frac{n_i(k)}{B \cdot S} [A - D_T(k)]$ .

*Remark 2:* In our model we have implicitly assumed that caches are saturated, which can be mathematically translated in:

$$\sum_{i=1}^M n_i(k) = B \cdot S. \quad (6)$$

Now, we can easily find the equilibrium point of system (5) by setting  $n_i(k+1) = n_i(k) = n_i^{eq}$ . We will refer to  $D_T^{eq}$  as the value of  $D_T$  at the considered equilibrium.

$$n_i^{eq} = \begin{cases} 1 + \frac{A}{D_T^{eq}} (p_i^{eq})^2 n_i^{eq} \pi_i \cdot H \cdot S, & \text{if } D_T^{eq} > A \\ 1 + (p_i^{eq})^2 n_i^{eq} \pi_i \cdot H \cdot S + n_i^{eq} \frac{A - D_T^{eq}}{B \cdot S}, & \text{otherwise.} \end{cases} \quad (7)$$

After some steps (See Appendix) it is easy to verify that, for  $D_T^{eq} > A$ :

$$n_i^{eq} = \begin{cases} g_1(\pi_i), & \text{if } \pi_i < \pi_0 \\ g_2(\pi_i), & \text{if } \pi_i \geq \pi_0, \end{cases} \quad (8)$$

where

$$g_1(\pi_i) = 1 + \frac{-\pi_i \cdot \left(\frac{2}{S} - 1 + \frac{\alpha}{\pi_i}\right) + \sqrt{\pi_i^2 \cdot \left(\frac{2}{S} - 1 + \frac{\alpha}{\pi_i}\right)^2 + 8 \frac{\pi_i^2}{S}}}{4 \frac{\pi_i}{S}} \quad (9)$$

$$g_2(\pi_i) = S \cdot \left(1 - \sqrt{\frac{\alpha}{\pi_i}}\right) \quad (10)$$

and  $\pi_0$  is chosen so that  $g_1(\pi_0) = g_2(\pi_0)$  and  $\alpha$  is computed as reported in the appendix.

For the second case in the system (7), i.e., when  $D_T^{eq} \leq A$ , we have:

$$n_i^{eq} = \begin{cases} l_1(\pi_i), & \text{if } \pi_i < \pi'_0 \\ l_2(\pi_i), & \text{if } \pi_i \geq \pi'_0, \end{cases} \quad (11)$$

where

$$l_1(\pi_i) = \frac{1}{1 - \pi_i \cdot H \cdot S - \beta} \quad (12)$$

$$l_2(\pi_i) = S \cdot \left(1 - \sqrt{\frac{\alpha'}{\pi_i}}\right) \quad (13)$$

and  $\pi'_0$  is chosen so that  $l_1(\pi'_0) = l_2(\pi'_0)$  and  $\alpha'$  is computed as described in the appendix.

In Fig. 2 it is possible to observe both the functions  $g_1$  and  $g_2$  compared to a reference proportional trend obtained assuming that content replicas are distributed at the equilibrium proportionally to their popularity (i.e.,  $n_i^{eq} = \pi_i B \cdot S / \sum_{i=1}^M \pi_i$ ),

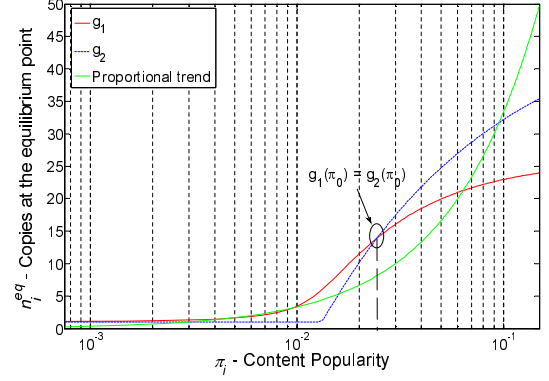


Fig. 2. Comparison between  $g_1$ ,  $g_2$  and the proportional trend ( $B=100$ ,  $M=200$ ,  $S=50$ ).

in the case of  $B = 100$ .

From this comparison we can evaluate the fairness in resource sharing with respect to content popularity. It is straightforward to note, in fact, that contents having a very small popularity track the proportional trend. Whereas, considering those having intermediate popularity, the rise of  $n_i$  is more than linear compared to the proportional one. Finally, for the most popular contents, the impact of the popularity on the number of copies in the network is sub-linear.

From figure 2 we can, also, balance the possible pros and cons of a CCN network. Firstly, this network behavior could limit the desired diffusion of some contents: the most popular content, with popularity  $\pi_{max}$  is cached in the network with almost the same number of copies of a content having popularity  $\frac{\pi_{max}}{2}$ . On the other hand, suppose that an *Interest Flooding attack* is taking place, in order to overwhelm the available bandwidth of the nodes that are believed to be the most likely sources of matching contents [1]. In this situation, the requested contents are considered very popular due to the enormous number of *Interests* that are generated. So that, if we focus on the relative section of the trend in Fig. 2, it is possible to understand how the previous attack could be mitigated by the CCN network itself, owing to the less space assigned to the popular contents compared to the proportional trend. We believe that in the future new strategy layers could be designed to achieve the desired level of fairness.

#### IV. VALIDATION

To validate the analytical model presented in the previous section, regarding the content diffusion in a CCN, a simple simulator using the Matlab software has been developed. In particular, we have simulated a random partially connected network, characterized by connectivity probability of  $8.0 \cdot 10^{-2}$ , with 50 nodes and 200 contents in different scenarios. The cache size of every node has been varied from 20 to 100 (also grid topologies have been considered, providing results similar to those we will present herein).

We have assigned to each content a different popularity, uniformly distributed in the interval  $[7.5 \cdot 10^{-5}, 0.15]$ . In every scenario it has been obtained a satisfying matching between

the theoretical trend and the simulated one (See figure 3), thus confirming the same considerations reported in the previous section.

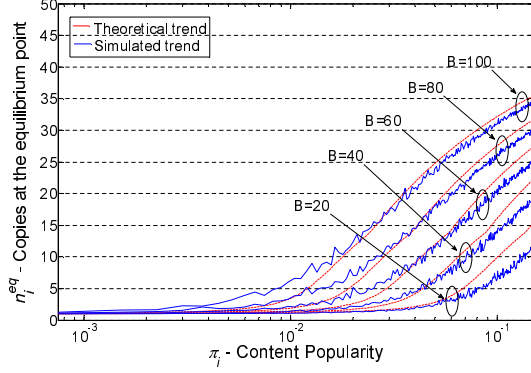


Fig. 3. Number of content replicas in the network according to their probability request ( $M=200$ ,  $S=50$ ).

From Fig. 4 it is also possible to note that the mean absolute relative error (obtained comparing the estimated  $n_i^{eq}$  with respect to the real one) becomes smaller and smaller as we increase the cache size: it ranges from 28.8% (in the case of  $B=20$ ) to 7% (in the case of  $B=100$ ). The reason of this improvement is in the approximation that has been made to estimate  $\alpha$  (see Appendix, section C). In fact, if we increase the cache size of every node,  $B$ , more and more, we decrease the number of contents for which we suppose the only seed copy to be present in the entire network (i.e.,  $i_0$ ). Doing this, the approximation (28) becomes better and better; so that we manage to estimate a good value for  $\alpha$ , through which the entire theoretical trend of eq. (8) perfectly matches the simulated one.

To confirm this explanation, we can directly solve the non-linear system (7) to find out the expression of  $n_i^{eq}$  for all the contents in the case of  $B=20$ . In this way, the relative mean error for  $B=20$  falls down, reaching the 10.0% (enough small if we compare it to the previous value of 28.8%).

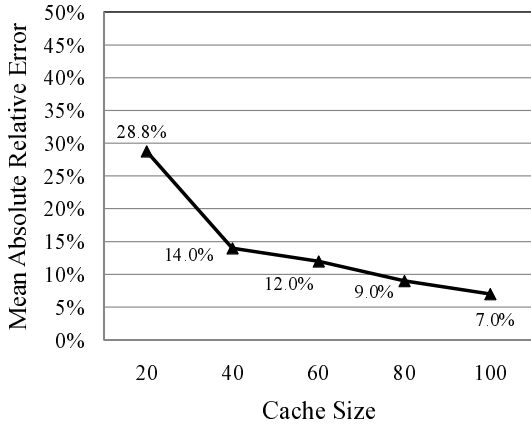


Fig. 4. Mean Absolute Relative Error ( $M=200$ ,  $S=50$ ).

## V. CONCLUSION

In this work, we have proposed a theoretical model to evaluate the fairness of a CCN network, focusing our analysis on content distribution according to their popularity. We have used the proportional trend as a point of reference, reaching the conclusion that contents having the largest popularity are not that advantaged by the CCN overlay (which privileges contents having intermediate popularities). This phenomenon could be considered both from a positive point of view (i.e. limiting the effects of an Interest flooding attack) and from a negative perspective (i.e., for the most popular contents there is not a completely fair allocation of the cache space in the network). Future research will investigate: (i) performance indexes, other than fairness, like the influence of different replacement policies over content availability, or the use of both explicit and implicit cache management techniques; (ii) the impact of contents with different sizes; (iii) the validation of the model against experimental CCN implementations.

## APPENDIX

In this appendix, we demonstrate how the close-form expression (8) can be derived from (7). Particularly, the resolution has been developed taking into account several cases.

### A. $D_T^{eq} > A$

1)  $n_i^{eq} \ll S$ : Substituting  $n_i^{eq} = 1 + \Delta_i^{eq}$ , with  $0 \leq \Delta_i^{eq} \leq S - 1$ , we can express the system (7) as:

$$\Delta_i^{eq} \cong \begin{cases} \frac{A}{D_T^{eq}} \cdot (p_i^{eq})^2 \cdot (1 + \Delta_i^{eq}) \pi_i \cdot H \cdot S, & \text{if } D_T^{eq} > A \\ (p_i^{eq})^2 \cdot (1 + \Delta_i^{eq}) \pi_i \cdot H \cdot S + (1 + \Delta_i^{eq}) \frac{A - D_T^{eq}}{B \cdot S}, & \text{otherwise.} \end{cases} \quad (14)$$

where we have approximated  $(S - n_i^{eq})^2 \cong (S - \Delta_i^{eq})^2$ .

It follows that:

$$\begin{cases} \frac{A}{D_T^{eq}} (p_i^{eq})^2 \left( \frac{1 + \Delta_i^{eq}}{\Delta_i^{eq}} \right) \pi_i \cdot H \cdot S = 1, & \text{if } D_T^{eq} > A \\ (p_i^{eq})^2 \left( \frac{1 + \Delta_i^{eq}}{\Delta_i^{eq}} \right) \pi_i \cdot H \cdot S + \left( \frac{1 + \Delta_i^{eq}}{\Delta_i^{eq}} \right) \frac{A - D_T^{eq}}{B \cdot S} = 1, & \text{otherwise.} \end{cases} \quad (15)$$

Now, we can consider the first equation of the system (15):

$$\frac{A}{D_T^{eq}} (p_i^{eq})^2 \left( \frac{1 + \Delta_i^{eq}}{\Delta_i^{eq}} \right) \pi_i \cdot H \cdot S = 1. \quad (16)$$

Imposing  $\alpha = \frac{D_T^{eq}}{H \cdot S \cdot A}$ , the previous equation becomes:

$$(p_i^{eq})^2 \left( \frac{1 + \Delta_i^{eq}}{\Delta_i^{eq}} \right) \pi_i = \alpha. \quad (17)$$

Considering that  $n_i^{eq} \ll S$ , and consequently  $\Delta_i^{eq} \ll S$ , we can simplify the  $(p_i^{eq})^2$  expression as follows:

$$(p_i^{eq})^2 = 1 + \left( \frac{\Delta_i^{eq}}{S} \right)^2 - 2 \cdot \frac{\Delta_i^{eq}}{S} \cong 1 - 2 \cdot \frac{\Delta_i^{eq}}{S}. \quad (18)$$

Substituting this approximation in the equation (17), we obtain:

$$2\pi_i \cdot \frac{\Delta_i^{eq}}{S} + \pi_i \Delta_i^{eq} \cdot \left( \frac{2}{S} - 1 + \frac{\alpha}{\pi_i} \right) - \pi_i = 0. \quad (19)$$

The solutions of the previous expression are:

$$\Delta_{i1/2}^{eq} = \frac{-\pi_i \cdot \left(\frac{2}{S} - 1 + \frac{\alpha}{\pi_i}\right) \mp \sqrt{\pi_i^2 \cdot \left(\frac{2}{S} - 1 + \frac{\alpha}{\pi_i}\right)^2 + 8 \frac{\pi_i^2}{S}}}{4 \frac{\pi_i}{S}} \quad (20)$$

Since  $0 \leq \Delta_i^{eq} \leq S - 1$ , we consider only the positive solution. In this way we have obtained a general solution well suited for the number of copies of less popular contents.

2)  $n_i^{eq} \gg 1$ : Starting from the system (7), if we consider only popular contents, we obtain a simplified solution. In fact, the first equation of the system (7) becomes:

$$(p_i^{eq})^2 = \frac{\alpha}{\pi_i} \left(1 - \frac{1}{n_i^{eq}}\right). \quad (21)$$

Since  $n_i^{eq} \gg 1$ , we can ignore the term  $1/n_i^{eq}$ , thus obtaining:

$$n_i^{eq} = S \cdot \left(1 - \sqrt{\frac{\alpha}{\pi_i}}\right). \quad (22)$$

Now, we have to consider that  $1 \leq n_i^{eq} \leq S$ . Hence, the probability of the  $i$ -th content should satisfy the following condition:

$$\pi_i > \frac{\alpha}{\left(1 - \frac{1}{S}\right)^2}. \quad (23)$$

### B. $D_T^{eq} \leq A$

This is the case in which the entire traffic generated in every time slot is less or equal than the available space in the network. If we consider the second equation of the system (7) we can split the resolution into two subcases:

1)  $n_i^{eq} \gg 1$ : Under this hypothesis the equation can be approximated as:

$$(p_i^{eq})^2 \cdot \pi_i H S + \beta \approx 1, \quad (24)$$

where  $\beta = \frac{A - D_T^{eq}}{B \cdot S}$ .

The previous expression leads to:

$$n_i^{eq} = S \cdot \left(1 - \sqrt{\frac{\alpha'}{\pi_i}}\right) \quad (25)$$

where  $\alpha' = \frac{1 - \beta}{H S}$ .

2)  $n_i^{eq} \ll S$ : In this case we can simplify and approximate the second equation of (7) in this way:

$$\left(\frac{n_i^{eq}}{n_i^{eq} - 1}\right) (\pi_i \cdot H \cdot S + \beta) = 1 \quad (26)$$

obtaining that:

$$l_1(\pi_i) = \frac{1}{1 - \pi_i \cdot H \cdot S - \beta} \quad (27)$$

### C. Estimating $\alpha$ , $\alpha'$ , $\pi_0$ , and $\pi_0'$

For  $D_T^{eq} > A$ , under the hypothesis that  $n_i^{eq} \gg 1$ , we could suppose that there are  $i_0$  contents in the network for which the condition (23) is not satisfied. Thus, we can simplify the

expression of the number of nodes containing each content:

$$n_i^{eq} = \begin{cases} 1, & \text{for } 1 \leq i \leq i_0 \\ S \cdot \left(1 - \sqrt{\frac{\alpha}{\pi_i}}\right), & \text{for } i_0 < i \leq M \end{cases} \quad (28)$$

Imposing the condition (6), we can calculate the value of the constant  $\alpha$  as:

$$\sqrt{\alpha} = \frac{i_0 + S \cdot (M - i_0) - B S}{S \cdot \sum_{i=i_0+1}^M \frac{1}{\sqrt{\pi_i}}} \quad (29)$$

Now, knowing the value of  $\alpha$ , it is possible to calculate both the equations in the system (8) and find out  $\pi_0$  too. The same consideration applies to the estimation of the value  $\alpha'$  for the case  $D_T^{eq} \leq A$ .

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