Analyzing Information Availability in ICN under Link Failures

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***Abstract*—Information-Centric Networks (ICNs) facilitate in-network caching, which has amongst others the advantage of providing higher information availability than traditional IP networks. This property is very beneficial in a variety of scenarios, ranging from node mobility to network disruptions and failures. However, a clear understanding of the extent to which information in ICNs remains available to the users in those scenarios as well as the impact of different ICN design choices (e.g. caching strategy and caching capacity) and network characteristics (e.g. topology) is currently lacking in literature. In order to fill this gap, we have developed an analytical model to study the information availability in ICNs when network disruptions occur. In particular, this model allows us to compute the probability that, under the occurrence of link failures, users are still able to retrieve the information they are interested in.**

The accuracy of our analytical model is demonstrated by comparing its results with results obtained by detailed simulations. These experiments also showed that, regarding the required computation time, our analytical model is considerably faster than simulation. The power of the analytical model is illustrated through many numerical examples on the information availability in ICNs under various link failure conditions, for different in-network caching strategies.

I. Introduction

High information availability through in-network caching is a key advantage of Information-Centric Networks (ICNs) over traditional IP networks. This property provides ICNs the potential to deal with situations characterized by intermittent or limited connectivity, for example when nodes go offline or links fail, or when nodes (or even network sub-parts) are mobile. However, although this advantage of ICNs is often mentioned in literature, see [2], [3], a clear understanding of the extent to which information in ICNs remains available in those circumstances is currently lacking. In particular, the influence of different design choices (e.g. caching strategy and capacity) and network characteristics (e.g. topology) on information availability is currently not addressed in literature.

Our work can be placed within this largely unexplored research field. Specifically, we focus on the information availability in ICNs under link failures. Our contribution is twofold: we (i) present an analytical modeling approach to study the information availability of hierarchically structured ICNs under link failures, and (ii) use this model to compute information availability in a realistic network with common architectural characteristics and traffic conditions. The analytical model builds on the work in [4], [5] on approximating cache-hit ratios in general web caching systems. In particular, we calculate the probability that a path from the end user to the requested content item (either in the original source or in a network cache) still exists given that a certain percentage of links has broken, and then combine this with the cache-hit ratio approximation of [5] to compute the probability that the user can still reach the required information. Comparison of results provided by this approach to results obtained from detailed system simulations shows that our analytical model is highly accurate. Furthermore, regarding computation times, the analytical model is much faster than simulation. Many numerical results for different ICN network scenarios and parameter settings are generated demonstrating the potential of our model. In particular, we present results obtained for two popular in-network caching strategies, Leave Copy Down (LCD) [6] and Leave Copy Everywhere (LCE) [7].

The remainder of this paper is structured as follows: Section 2 provides background on ICN and information availability in ICN, including references to related work. In Section 3, we elaborate on the main scenario and modelling assumptions considered in this paper. With this in mind, in Section 4 we present our analytical modeling approach to deriving the information availability in ICNs under link failures. The analytical model will be validated in Section 5, before moving on to the conclusions and further research in Section 6.

II. Background and related work

The key functionalities that need to be addressed by ICNs are naming, name resolution and data routing, caching, mobility and security, see [2] [3]. In addition, according to [11], ICN should also achieve the following design principles: scalability, availability, reliability, network management simplicity, Quality of Service, loosely coupling system and flexible business models. In this paper we will focus on information availability in ICNs. By definition, availability is the proportion of time that a system is in a functioning condition. This concept is closely related to network robustness, the extent to which a network can deal with perturbations imposed onto the network, see for instance [12]. Typically the network robustness is expressed as the fraction of the network that is still connected, given the failures of a certain percentage of the network elements. In this paper we interpret information availability as *the percentage of information requests from the end-users, that is successfully delivered, given a disturbance (i.e. link failures) in the network.*

Several papers have assessed the performance of ICNs regarding the caching strategies used. For instance, Chai et al. [13], have compared the performance of the so called Networking Named Content (NNC) approach, where content is cached in every node it traverses along the delivery path, with a strategy that caches the content in a subset of nodes along the content delivery path. Typically the performance of the different caching strategies is assessed in terms of measures such as the hop reduction ratio and the server hit reduction ratio. Ramaswamy [14] also considered the expected hop-count for generic ICNs. Although obviously, there is a relation between hop-count and information availability for ICNs, to the best of our knowledge, this relation is not made explicit by any paper.

Also, several papers studied security aspects of ICNs, see for instance [15], [16]. Although the triad of confidentiality, integrity, and availability is at the heart of information security, see [17], availability of information in not covered by these authors. Thus, we have found no papers that compare different caching strategies within ICNs for the information availability performance metric that we consider. In particular, we will consider this metric under the condition of unreliable links, i.e. we assume that each link i is available with a probability p_i and we are interested in estimating the probability that a certain piece of content can be accessed over the network. In terms of mathematics, this probability is related to a so-called k-terminal reliability, i.e. the probability that a given set of k nodes in the network is connected, given independent failures in the network, see [18].

III. Modelling assumptions

We consider an hierarchical network, in which different layers can be distinguished. In such a network, each shortest path from top to bottom traverses exactly one node from each layer. We model the network as an undirected hierarchical graph $G = (V, E)$, with vertices V, and edges E.

We define the set of content sources (i.e. original data producers) as $S \subset V$, and the end-users as $T \subset V$. The set of nodes that are not sources nor end-users represent the routers R, with $R = V \setminus (T \cup S)$. Specifically, the sources reside on the top layer (l_{n-1}, with n being the total number of layers), the end users reside on the bottom layer (l_0), and the routers reside in the layers in between (from l_1 until l_{n-2}). An example of such a hierarchical network is given in Figure 2.

Content items are defined by the following set: $D = \{d_1, d_2, \cdots d_M\}$; each content item is allocated to exactly one $s_i \in S$. Here M denotes the total number of content items.

Content is being requested according to a Poisson arrival process. In this arrival process, the content popularity follows the Zipf's law, where $\lambda(d_i)$ is the exogenous Poisson process describing the arrival rate for content of type d_i. Also, we will need the arrival rate of requests for content of type d_i at layer k, denoted as $\overline{\lambda}_k(d_i)$.

For the purpose of simplicity, we assume that content items have all the same size and that all routers $r \in R$ have the same caching capacity C. As caching strategy, we use both Leave-Copy-Down (LCD) and Leave-Copy-Everywhere (LCE), and we employ Least Recently Used (LRU) as cache replacement strategy.

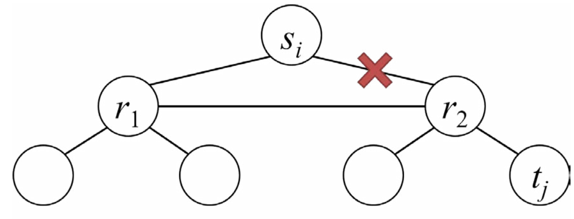

Fig. 1. The shortest path from the source s_i to the user t_j passes through the edge (s_i, r_2). In the moments immediately after this path fails, while the routing layer computes another path (e.g. via the edges (s_i, r_1) and (r_1, r_2)), s_i is temporarily unreachable by t_j.

Once end user t_j requests content item d_k, a search is performed along the shortest path from t_j to the source s_i to which d_k is assigned. If the content item is found in one of the routers along the path, it is retrieved from there and returned to the requesting end user (*cache hit*). Our model will take into account the probability that the content item is found at a specific layer. Conceptually, we will need to consider two variables for this, $P_{hit}(k, d_i)$: the probability of a hit of object d_i in the cache at layer k, and $P_{in}(k, d_i)$: the time average probability that object d_i is in a cache at layer k. Note that the definition of the event that there is a hit at layer k means that there are cache misses at layer $i, i = 1, \cdots, k-1$ and a cache hit at layer k.

If the content is not retrieved at any of the caches (*cache miss*), d_k will be retrieved from s_i. If one of the edges along this shortest path breaks, our model assumes that s_j can no longer be reached. In reality, s_j might still be reachable via another path, as shown in Figure 1. However, it will take some time for the routing layer to discover the alternative path, making s_i *de facto* unreachable by t_j in the moments immediately after the link failure. Our model captures the information availability just after this link failure.

IV. Information availability analysis

To model information availability under link failures, we proceed in two steps. Firstly, we compute the cache hit ratio per layer. Secondly, we compute the probability that a path between the end user and the location of the cache hit exists. Knowing the probability that a content item is available in a certain layer as well as the probability that a path to that layer exists, we can calculate the probability of a successful content delivery.

A. Step 1: modeling the cache hit ratio per layer

Our first step is computing the probability of finding the requested item in a cache. This aspect is embedded in the cache hit ratio. The cache hit ratio of the LCE and LCD strategies can be approximated, using the set of equations of [4].

As an example, we show below the equations for the approximation of the cache hit ratio for layers one and two, per content item, in the case of the LCD strategy, as obtained from [4]. In particular, the equations involve $P_{hit}(1, d_i)$, $P_{hit}(2, d_i)$ and $P_{in}(1, d_i)$, defined in the previous section.

$$P_{hit}(1,d_i) \approx P_{in}(1,d_i) = [(1-P_{in}(1,d_i))P_{hit}(2,d_i) + P_{in}(1,d_i)] \cdot \left(1 - e^{-\overline{\lambda}_1(d_i) t_C^{(1)}}\right)$$
$$P_{in}(2,d_i) = 1 - e^{-\overline{\lambda}_2(d_i) t_C^{(2)}} \tag{1}$$

$$P_{hit}(2,d_i) = \begin{cases} \left(1 - e^{-\overline{\lambda}_2(d_i)\left(t_C^{(2)} - t_C^{(1)}\right)}\right) e^{-\overline{\lambda}_2(d_i) t_C^{(1)}} \\ +1 - e^{-\overline{\lambda}_2(d_i)(1-P_{hit}(2,d_i)) t_C^{(1)}}, \text{if } t_C^{(2)} > t_C^{(1)} \\ 1 - e^{-\overline{\lambda}_2(d_i)(1-P_{hit}(2,d_i)) t_C^{(2)}}, \text{otherwise} \end{cases} \tag{2}$$

where $d_i \in D$, and $\overline{\lambda}_2(d_i) = \lambda(d_i)(1 - P_{hit}(1,d_i))$. Furthermore, $t_C^{(j)} (j \in \{1,2\})$ are the roots of

$$\sum_{d_i \in D} P_{in}(j,d_i) = C, \tag{3}$$

where C is the cache size.

The above equations can be generalized to obtain expressions for $P_{hit}(k,d_i)$ with $k > 2$. For this we need to adjust the arrival process of information requests at layer k as follows $\overline{\lambda}_k(d_i) = \overline{\lambda}_{k-1}(d_i)(1 - P_{hit}(k-1,d_i))$, with $\overline{\lambda}_1(d_i) = \lambda(d_i)$, see [4].

This approach can be extended to other caching strategies and other network topologies (see for example [4]).

From the above equations, we can derive the cache hit ratio for each layer k over all content items, as follows:

$$P_{HIT}(k) = \sum_{d \in D} \left(\overline{\lambda}_k(d) * P_{hit}(k,d)\right). \tag{4}$$

B. Step 2: modeling layer reachability under link failures

Next, we model the probability that a layer can be reached, given a disturbance in the network. Let f be the fraction of links that fails due to such a disturbance. If there is only one unique path between 2 consecutive layers, the probability that a path exists between these two layers is given by

$$P(\text{path}) = 1 - f. \tag{5}$$

If there are two (independent) shortest paths between two consecutive layers in the network, then the probability that a path exists between the two consecutive layers is given by

$$P(\text{path}) = 1 - f \cdot \frac{f \cdot L - 1}{L - 1}, \tag{6}$$

where L is the total number of links in the network. For large L this probability can be approximated as follows:

$$P(\text{path}) = 1 - f^2. \tag{7}$$

Note that according to our definition of hierarchical networks, these paths always have length one. Now, the probability that a certain layer k in the network can be reached, which we denote as $P(\text{path to layer k exists})$, is computed by multiplying the probability of reaching each consecutive layer. In case that only parts of this path are unique, Equation 5 and 7 can be combined to derive $P(\text{path to layer k exists})$.

C. Combining steps 1 and 2 to model information availability

The information availability can now be derived combining the cache hit ratios for each layer (step 1), with the probability of reaching each layer (step 2). This leads to the following formulation

$$P(\text{successful request}) = \sum_{k=1}^{n-1} \left(P(\text{path to layer k exists}) * P_{HIT}(k)\right), \tag{8}$$

where n is the number of layers from the end users to the sources in the hierarchical network, and $P_{HIT}(k)$ is the cache hit ratio per layer over all content items (Eq. (4)). We observe that the cache hit ratio for the source layer $n-1$ is equal to the probability of a cache miss in all other layers

$$P_{HIT}(n-1) = 1 - \sum_{k=1}^{n-2} P_{HIT}(k). \tag{9}$$

Finally, in a network without caching (i.e. where $C = 0$), the information availability is simply the probability that a path to the source (layer $n-1$) exists.

$$P(\text{successful request}) = P(\text{path to layer } n-1 \text{ exists}) \tag{10}$$

V. Model Validation

To assess the validity of our approach, we have evaluated our model using the Icarus simulator [1]. The Icarus simulator is designed explicitly to test caching strategies in ICN. Icarus is very scalable, for small-to-medium network topologies. However, for realistic networks (> 1000 nodes and > 1500 links), we note that simulation times grow quite rapidly (hence the need for model-based analysis).

We have evaluated our model in two different scenarios. In the first scenario, we consider a simple setup, characterized by an ideal tree topology and the standard ICN caching strategy, LCE [7]; in the second scenario, we consider a more complex yet more realistic setup, using an IPTV-like topology in combination with the LCD caching strategy, which resembles the way in which caching decisions occur in modern IPTV systems. Our validation setup and results are presented in the paragraphs that follow.

A. Setup

In the first scenario, we use a binary tree with 5 layers (31 nodes in total). In this case, the top node is a source S (at l_4), the lowest 16 nodes are end users T, and the 14 nodes on the layers l_1, l_2 and l_3 are routers R. Further, we assume that the content population has size 500, that the caching strategy LCE is used and that the cache size takes the following values: 1, 5, 20, 50, 100, 200, 250, 450.

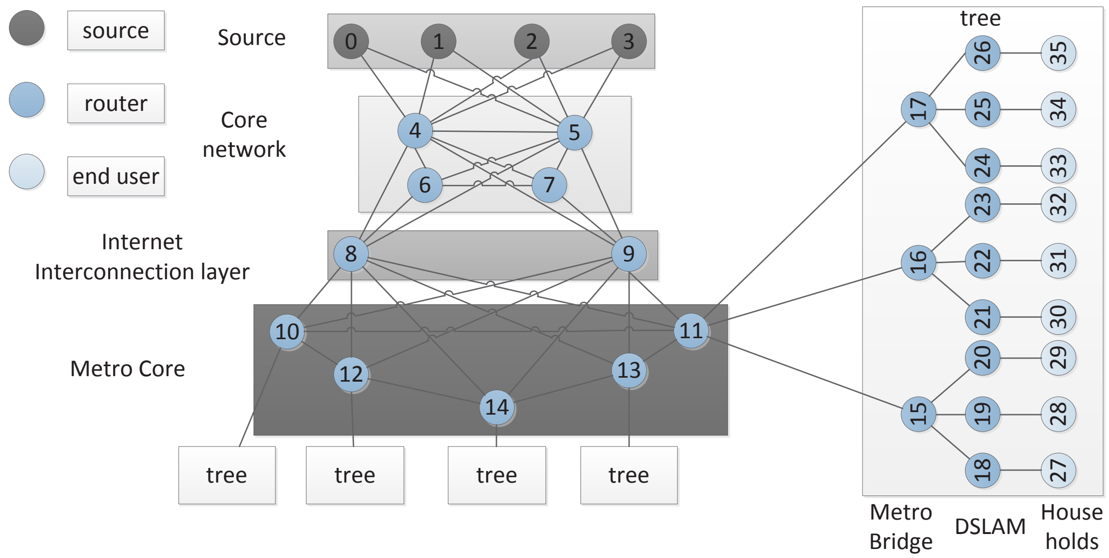

Fig. 2. IPTV-like network topology used for the second validation scenario (36 nodes)

In the second scenario, we consider an IPTV-like network topology, structured according to the model of the ITU [8], and inspired by real architectures deployed by European network operators. This topology has 36 nodes and 7 layers, as reported in Figure 2. For this topology, we assume a content set composed of 1000 items (typical catalogue sizes in IPTV networks range from 5000 to 10000 [9], [10]; however, after the 1000 most popular items, we have observed that the effects on the results are negligible due to the long tail of the popularity distribution). We use the LCD caching strategy, with cache size taking the following values: 1, 5, 20, 50, 100, 250, 450, 650, 800, 900. In IPTV networks a copy of the content gets cached more and more down the hierarchy as requests for it increase, which is similar to how LCD in ICN works.

For both scenarios, the popularity of the items in the content set follows the Zipf's law, with $\alpha = 0.8$.

For every specific configuration, we do 10 simulation runs. To make sure that the system has reached a steady state when we measure it, we use 100000 warmup requests and 10000 measured requests for each simulation run. Within each simulation run, we perform 10 rounds, where at the end of each round, links are broken and the corresponding cache hit ratios and information availability are computed; the links are then restored before performing the next round. Hence, effectively, for each configuration we obtain 100 values for cache hit ratio and 100 for information availability, whose averages are taken as simulation results.

The execution time of each simulation run is in the range of minutes. Solving the set of equations is in the range of seconds for most configurations.

B. Results

1) Tree topology, LCE caching strategy: For the probability of an existing path to layer k, we make use of Equation 5 only,

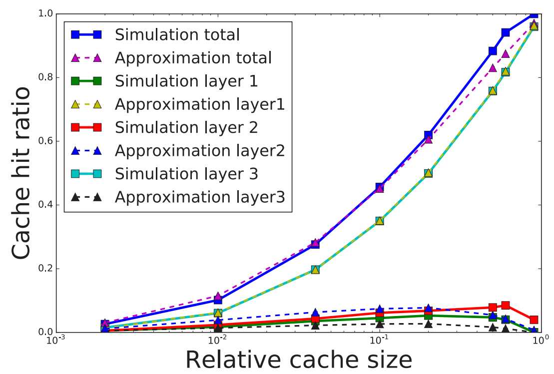

Fig. 3. Cache hit ratio vs cache size for the binary tree topology (LCE caching strategy, relative cache size = C / (number of content items))

since all paths from the source to the end users in a tree are unique. By multiplying the probabilities of the existence of a path between each consecutive layer, we obtain:

$$P(\text{path to layer k exists}) = (1-f)^k \tag{11}$$

The probability of a successful request (= information availability), applying Eq. (8), is as follows

$$P(\text{succesful request}) = \sum_{k=1}^{3} (P(\text{path to layer k exists}) \cdot P_{HIT}(k)) + P(\text{path to layer 4 exists}) \cdot (1 - \sum_{k=1}^{3} P_{HIT}(k)), \tag{12}$$

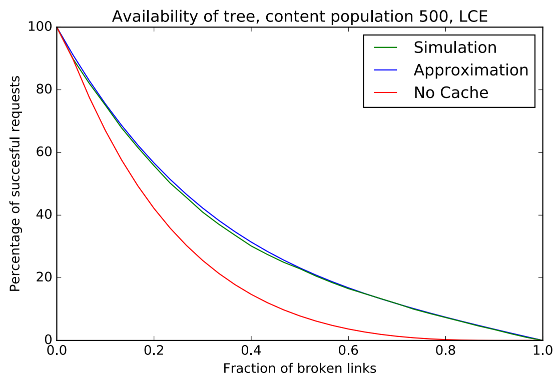

Fig. 4. Information availability for a binary tree topology (LCE caching strategy, C = 20)

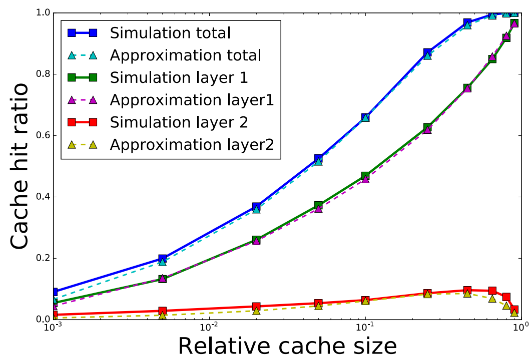

Fig. 5. Cache hit ratio vs cache size for the IPTV-like topology (LCD caching strategy, relative cache size = C / (number of content items))

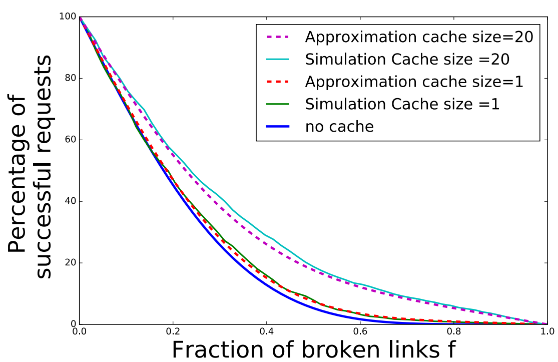

Fig. 6. Information availability for the IPTV-like topology (LCD caching strategy, C = 20)

where the cache hit ratio for the source (layer 4) is equal to the probability of cache miss in all other layers of the tree.

For the case without caching, we have (from Eq. (10))

$$P(\text{successful request}) = (1-f)^4. \tag{13}$$

Figure 3 pictures the total cache hit ratio as well as the cache hit ratios at layers 1 to 3, for the tree topology.

The information availability as a function of the broken links is pictured in Figure 4, for a cache size of 20. For a small fraction of broken links (for instance 5%) the relative increase for the information availability versus the case of no caching (hereafter referred to as *gain*) is 5%. For a medium fraction of broken links (for instance 20%) the gain is 14%. For a large fraction of broken links (for instance 50%) the gain becomes 15%.

2) IPTV-like topology, LCD caching strategy: For the first three layers, the probability that there exists a path to a specific node in the layer k, given that a fraction f of the nodes is being broken, is equal to $P(\text{path to layer k exists}) = (1-f)^k$, since these layers have a tree structure. For layers l_4 and l_5 as well as for the sources (l_6), we have

$$P\,(\text{path to layer } k \text{ exists}) = ((1-f)^3 \cdot (1-f^2)^{k-3}). \tag{14}$$

The information availability formula consists of the probability that a path to a certain layer exists times the probability of a cache hit (see Eq. (8)). Hence, the information availability is equal to:

$$P(\text{successful request}) = \sum_{k=1}^{5} (P(\text{path to layer k exists}) \cdot P_{HIT}(k)) \\ + P(\text{path to layer 6 exists}) \cdot (1 - \sum_{k=1}^{5} P_{HIT}(k)), \tag{15}$$

where the cache hit ratio for the sources (layer 6) is equal to the probability of cache miss in all other layers of the topology.

Combining Eqs. (15) and (14), we obtain

$$P(\text{successful request}) = \left(\sum_{j=1}^{3} (1-f)^j \cdot P_{HIT}(j)\right) \\ + \left(\sum_{k=4}^{5} ((1-f)^3 \cdot (1-f^2)^{k-3}) \cdot P_{HIT}(k)\right) \\ + \left(((1-f)^3 \cdot (1-f^2)^3) \cdot \left(1 - \sum_{i=1}^{5} P_{HIT}(i)\right)\right) \tag{16}$$

For the case without caching, we have (from Eq. (10))

$$P(\text{successful request}) = (1-f)^3 \cdot (1-f^2)^3. \tag{17}$$

Figure 5 plots cache hit ratios for the IPTV-like topology of Figure 2 for different cache sizes. Here, we can distinguish between the total cache hit ratio and the cache hit ratios for layer l_1 and l_2.

The information availability for different cache sizes (0, 1 and 20) is pictured in Figure 6. For a small fraction of broken links (for instance 5%) the gain in information availability (C = 20) is 4%. For a medium fraction of broken links (for instance 20%) the gain is 12%. For a large fraction of broken links (for instance 50%) the gain becomes 15%.

Also, for both topologies (tree and IPTV-like), we observe that the gain in information availability decreases as the fraction of broken links grows beyond 50%.

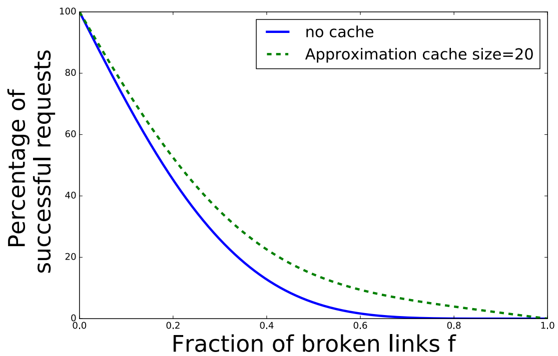

Fig. 7. The approximated information availability for the larger IPTV-like network topology (LCD caching strategy)

VI. Modeling Information Availability in a Large IPTV-like Network

In this section, we use our model to analytically quantify information availability under link failure for a larger IPTV network. This network is similar to the network of Figure 2 (same amount of layers), but has more nodes on the lower layers. Specifically, the source layer (l_6), core layer (l_5) and internet interconnection layer (l_4) remain the same. However, the metro core layer (l_3) is extended to 8 nodes, each having 5 disjoint children nodes on the metro bridge layer (l_2), leading to 40 metro bridge nodes in total. Each metro bridge node has 5 disjoint children on the DSLAM layer (l_1) resulting in a total of 200 DSLAM nodes. Each DSLAM is in turn connected to 6 distinct house holds (l_0), yielding to a total of 1200 house holds. To summarize, this topology has 1458 nodes: 4 sources S, 254 routers R, and 1200 end users T.

We use a content set of 1000 items (requested using a Zipf distribution with $\alpha = 0.8$) and the LCD caching strategy (cache size $C = 20$). Figure 7 reports the analytically computed information availability, as a function of broken links, for this network in this setup. The network is too complex to perform a simulation here, hence the figure only depicts the analytically computed results. Also in this case, the information availability gain due to caching grows as the fraction of broken links grows towards 50% (from a 2% gain when the broken links are 5% to a 10% gain when the broken links are 50%). For larger fraction of broken links, the effect of caching offers diminishing returns on the information availability gain.

VII. Conclusion and Future Research

In this paper we have shown how to analytically compute the information availability in a hierarchical ICN network, when a fraction of the links fails. We have validated our approach using detailed system simulations, for various topologies and in-network caching strategies.

Many numerical results have been generated, demonstrating the potential of the analytical model for analyzing ICN information availability under link failures. We have, for example, analyzed the trend of information availability as a function of the fraction of broken links. Our analysis shows that the relative increase in the information availability due to caching grows with the faction of broken links. When, however, the fraction of broken links grows beyond 50%, the effect of caching has diminishing returns. We have also shown that our model can easily handle networks consisting of about 1500 nodes, a size currently too large for the simulator.

Based on this work, we see several directions for further research. For example, it would be interesting to model information availability for non-hierarchical networks as well. Furthermore, it would be interesting to consider the impact of link failures on routing, and incorporate rerouting schemes in the analysis. The models to be developed will be extremely useful in assessing information availability in ICNs and how to improve it, as well as in determining in which cases, based on information availability, an ICN approach should be preferred over a traditional IP-based approach.

References

[1] L. Saino, I. Psaras and G. Pavlou, "Icarus: a Caching Simulator for Information Centric Networking (ICN)", *SIMUTools*, 2014.

[2] J. Kurose, "Information-centric networking: The evolution from circuits to packets to content", *Computer Networks 66 112120*, 2014

[3] A.V. Vasilakos, Z. Li, G. Simon, W. You, "Information centric network: Research challenges and opportunities", *J. of Network and Computer Application, 52, 1-10*, 2015

[4] M. Garetto, E. Leonardi, V. Martina, "A unified approach to the performance analysis of caching systems", *ACM Transactions on Modeling and Performance Evaluation of Computing Systems*, 2016

[5] H. Che, Y. Tung, and Z. Wang, "Hierarchical web caching systems: Modeling, design and experimental results", *IEEE Journal on Selected Areas in Communications*, 2002

[6] N. Laoutaris, H. Che, I. Stavrakakis "The LCD interconnection of LRU caches and its analysis" *Performance Evaluation, vol. 63, no. 7*, 2006

[7] V. Jacobson, D.K. Smetters, J.D. Thornton, M.F. Plass, N.H. Briggs, and R.L. Braynard, "Networking named content" *ACM CoNEXT*, 2009

[8] *IPTV architecture, ITU* https://www.itu.int/dms_pub/itu-t/oth/06/16/T06160000070001PDFE.pdf Retrieved on 02/05/2017

[9] *videoland catalogue* https://filmaanbieder.nl/videoland/aanbod/ Retrieved on 02/05/2017

[10] *KPN IPTV on-demand catalogue* https://www.kpn.com/televisie/voordelen/on-demand-kijken.htm Retrieved on 02/05/2017

[11] F. Almeida, J. Loureno, "Information centric networks-design issues principles and approaches", *Int. J. Latest Trends Comput., vol. 3, no. 3, pp. 58-66*, 2012

[12] R. Albert, H. Jeong & A.L. Barabasi, "Error and attack tolerance of complex networks", *Nature 406, 378-382*, 2000

[13] W.K. Chai, D. He, I. Psaras, G. Pavlou, "Cache less for more in information-centric networks", *in: Proceedings of the 11th International IFIP TC 6 Conference on Networking, IFIP12*, 2012

[14] Venkatesh Ramaswamy, "Modeling and Performance Analysis of Information-Centric Networks", *Proc. of 25th International Conference Computer Communication and Networks (ICCCN), 1-4 Aug. 2016, Waikoloa, HI, USA*, 2016

[15] E. G. AbdAllah, H. S. Hassanein, M. Zulkernine, "A Survey of Security Attacks in Information-Centric Networking", *IEEE Communication Surveys & Tutorials, VOL. 17, NO. 3*, 2015

[16] George Xylomenos, Christopher N. Ververidis, Vasilios A. Siris, Nikos Fotiou, Christos Tsilopoulos, Xenofon Vasilakos, Konstantinos V. Katsaros, and George C. Polyzos, "A Survey of Information-Centric Networking Research", *IEEE Communications Surveys Tutorials, VOL. 16, NO. 2, Sec. Quarter*, 2014

[17] C. Easttom, "Computer Security Fundamentals (2nd Edition)", *Pearson Education*, 2011

[18] C. J. Colbourn, "The Combinatorics of Network Reliability",*Oxford University Press*, 1987