An Energy-efficiency Assessment of Content Centric Networking (CCN)

Technical Report

Muhammad Rizwan Butt
Electrical & Computer Engineering
Mcgill University
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***Abstract*—Energy-efficient networking is a topic that is gaining importance at a rapid pace. Energy-efficiency is considered to be one of the important parameters in designing a new networking architecture. Content-Centric Networking (CCN) is a new networking architecture proposed for the future Internet. It has the potential to provide better results in terms of bandwidth usage, scalability and security as compared to the current IP-based architecture. In this report, we present an intuitive model for content dissemination in CCN and conduct an energy consumption analysis of it compared to IP-based network in a video streaming scenario. We consider two types of energy consumption. First, we calculate the emergy (i.e., the energy required to manufacture) of the network devices. Second, we calculate the energy required to operate the network devices for streaming the video. CCN network devices (routers) have a higher emergy and require more energy to operate compared to the IP-based network devices, however by exploiting their caching capability substantial energy benefits can be reaped. The emergy is a one time cost and does not change once the network is deployed. We propose a mechanism to reduce operation energy consumption for CCN. The results obtained by performing energy analysis on CCN and IP-based networks show that the CCN-based network with the proposed mechanism consumes less energy compared to the IP-based network.**

***Index Terms*—CCN, Energy efficiency.**

I. Introduction

Today the traffic generated by Video on Demand (VoD) accounts for a major fraction of the Internet's traffic. The demand for distribution of content through Internet is increasing day by day and the current IP-based Internet architecture is not capable to sustain this demand for long. This development poses questions e.g., how the existing Internet will handle bandwidth usage and scalability issues for future content dissemination networks? Substantial research efforts have been made in the recent years to come up with a better networking architecture for the future Internet. At present at least three ongoing projects address this issue using different networking paradigms [1], [2], [3]. Among these recently proposed architectures, Content-Centric Networking (CCN) appears to have the potential of incrementally replacing the existing IP based architecture.

In this report, we provide a brief discussion about CCN and undertake a comparative study of CCN and IP-based network in terms of energy consumption in a VoD scenario. We consider a dedicated video streaming application where clients download content (movie) through a CCN and an IP-based network respectively. A probabilistic model for content-dissemination in CCN is derived and the energy consumption for both IP and CCN-based network is estimated. To calculate the energy consumption for both IP and CCN, manufacturing and operation energy costs for all the network devices used in this analysis are calculated. We use the notion of emergy as used by Raghavan et al. in [4] to calculate the manufacturing energy of the network devices. The network routers in CCN have the capability to cache the content. This feature allows the CCN network to operate at a lower rate as compared to IP-based implementation in a VoD scenario. We argue that switching a network device to sleep mode in order to save energy consumption is not a feasible option for a content dissemination network (e.g., VoD) as this can introduce delays [5] while streaming a video. Therefore, we propose that CCN routers should make use of rate adaptation according to the load requirement of the network to reduce energy cost [6].

The rest of the report is organized as follows. In Section II we present literature review. Section III describes the network model and the cost calculation procedure for the energy analysis. Section IV describes a use case VoD scenario for the energy analysis of CCN and IP-base network. Section V reports results from our energy analysis for CCN and IP-based networks. Section VI concludes the report and provides directions for the future work.

II. Related Work

There has been much recent work addressing the need to develop better architecture for the future Internet. To the best of our knowledge there are at least three projects [1], [2], [3] as mentioned earlier which try to address this issue.

Project CCNx was initiated to develop, promote, and evaluate a new approach to communication architecture called content centric networking. This new architecture is the focus of a long-term research and development program. There are interesting problems in many areas of CCNx that are still to be solved and fully realized. The details about the project can be found in [7]. Jacobson et al. in [1] have tried to exploit the fact that today's Internet is predominantly a distribution system where users are more interested in the distribution of the content rather than point to point communication between hosts, but ironically the Internet architecture was meant to share resources, not data. The authors have proposed Content-Centric Networking (CCN) which is a networking architecture built on similar principles as existing IP architecture but instead of using location based (host to host) communication to retrieve data CCN uses named data. There are two types of packets used: *Interest* and *Data*. A consumer broadcasts *Interest* and any node within its communication range having the required data sends back the *Data* packet. The flow balance of CCN's *Interest* and *Data* packets is similar to TCP's *Data* and *ACK* packets but the CCN model provides many-to-many multi point delivery which is not possible with TCP.

IP based protocols cannot take advantage of more than one interface on a mobile device while CCN can. "CCN talks *about* data, not *to* nodes" [1], so it does not need to bind IP address to MAC address, hence rich connectivity and mobility can be achieved by exploiting multiple interfaces. Each node gets per-prefix, per-interface performance information for adaptively choosing the "best" interfaces for forwarding Interests matching some prefix.

Ahlgren et al. in [2] introduce Network of Information (NetInf). It is an information-centric global networking architecture which delivers content only to the consenting nodes, as a result reduces unwanted traffic and provides host independent communication. NetInf is based on a publish/subscribe communication paradigm similar to CCN but its implementation over the existing IP based Internet infrastructure remains an open research problem.

Bouabene et al. in [3] have presented a novel, flexible and extensible network framework to interconnect multiple heterogeneous networks in an autonomic way. Autonomous Networking Architecture (ANA) introduces generic abstractions that support network heterogeneity and evolution. These abstractions are the *functional blocks*, the *information channel* and the *information dispatch points*. *Functional blocks* provide the information processing in ANA and represent the protocols of any other functionality implemented in the network. The *information channel* represent an abstraction for communication channels that allow nodes and *functional blocks* to communicate with each other. This communication is based on a standardized API that offers a basic set of methods to exchange information such as *ana publish*, *ana unpublish*, *ana resolve*, *ana lookup* and *ana send*. Finally, the *information dispatch points* are the access points that address the previously defined elements like *functional blocks* or *information channels*. Each element is bound to an *information dispatch point* and can see the change in binding dynamically if needed.

All communication within ANA is via massage passing between *functional blocks*. The *functional blocks* have private memory and data that cannot be accessed by other *functional blocks* so there is no risk of having malicious software that creates deadlocks by never releasing mutual exclusion for shared resources. Proliferation of malicious code in the ANA is possible as there is no mechanism in place to handle runtime security. This paper presents a clean-slate architecture for future Internet which is not a feasible option as it would be virtually impossible to replace millions of network devices which populate today's Internet. Also the authors do not report any comparative studies with current research in this field e.g., [1], [3].

All of these architectures are new, and very little work has been done to compare which one of them would be the way forward for the future Internet. From the perspective of networking community, an architecture which has the ability to be backward compatible would definitely be a better choice. CCN is the only architecture among these three which appears to have this quality [8]. Shifting the existing Internet to CCN would be a large scale transition. There are several important aspects which need to be taken into account before making this transition and energy efficiency is one of them.

Seetharam et al. in [9] have provided a green (carbon footprint and energy consumption) analysis of IP-based movie streaming application with the shipping based movie distribution system. They provide a detailed discussion about calculating the operational and manufacturing energy consumption of network devices in IP-based network. Raghavan et al. in [4] provide an approximate analysis of the Internet's energy consumption. They have used the notion of emergy (embodied energy), the energy required to construct the Internet. This concept of emergy is actually equivalent to the concept of manufacturing energy consumption used by Seetharam et al. in [9]. We take the motivation from [9], [4] to estimate the energy consumption for CCN and IP-based network devices.

Antonakopoulos et al. in [6] argue that the current Internet backbone networks are over-provisioned so they have much more capacity than the average traffic. Significant daily variation in the traffic load and redundant capacity to cater problems such as link failures are the two main reasons for this over-provisioning. However, the energy consumption of current network elements (routers and switches) appears to be largely constant. This provides an opportunity to reduce energy consumption of the Internet backbone network by making it more sensitive to traffic load. They present the notion of power-aware routing with rate-adaptive network devices and demonstrate that the combination of rate-adaptivity and power-aware routing saves a significant fraction of network power, for a wide variety of network topologies, traffic loads, and startup values. Power-aware routing involves a fairly simple model of network power use, where power consumption is attributed to links. A link can be turned off, in which case power use is zero, or a fixed startup power is required to turn on the link. This may be a feasible option for running different applications on the Internet but as we have discussed earlier, in case of a VoD it is not affordable to turn off a link. So for our analysis we will try to benefit from rate adaptation alone. Sergiu et al. in [5] presents rate adaptation using rate scaling and sleep-state for network devices. In case of rate scaling, the clock frequency of a network device changes over time to match the traffic processing rate of the device with the input traffic load. The rate adaptation proposal presented by Sergiu et al. rely on global network coordination to maximize energy savings. It requires the full cooperation of large blocks of the network. Such adjustments throughout the network are impractical. Another trade-off of the rate adaptation scheme described in [5] is that all state transitions take time to complete. This will introduce unwanted delays in the network.

Francini et al. in [10] addresses these issues by focusing exclusively on deployment models where network coordination is not required. They devise a simple method for dividing the network into rate adaptation domains that are completely isolated from one another in terms of controlling their operating states. To handle delays due to state transitions a hybrid rate adaptation scheme is defined. The authors introduce classes of state-selection policies that enforce deterministic bounds on extra buffers and delays, providing tight upper and lower bounds on the average power consumption of network devices with rate adaptation capabilities. The details of improving rate adaptation schemes is out of scope of this report.

For our analysis we can use simple rate scaling of [5] or adaptive link rate techniques described by Chamara et al. in [11], [12]. Chamara et al. provide link utilization based threshold policy. When the link utilization threshold policy is implemented on the network routers, each router monitors the amount of traffic passing through it. This information is used to define a threshold to adjust the link rate to a higher or a lower value accordingly.

Lee et al. in [13] propose architecture for energy-efficient CCN router. They claim that energy benefits can be reaped by deploying these routers throughout the Internet incrementally. They have undertaken an energy analysis for CCN without modeling CCN. There energy analysis only considers the energy cost when clients are downloading content and all the network devices are operating at their peak power ratings. No notion has been provided about the energy cost incurred by manufacturing and powering of the extra cache memory of the CCN routers. They suggested that according to the network traffic requirements the CCN routers can be switched on or off to save energy consumption.

III. Energy Analysis

A. Network Model

To compare the energy consumption in IP and CCN-based networks, a simple network model is considered in which a video server provides streaming services to the clients. A general tree based network topology has been chosen as shown in Figure 1. The goal is to compare the energy consumption in a video streaming application both through IP and CCN based networks and identify which network is more energy efficient.

In the case of an IP based network, the probability of finding content on any given level is always zero as the routers cannot cache the content. However for CCN, each router has a caching capability so the probability of finding content on each level is non-zero. Hence this probability has to be defined to further analyze the system.

Consider a CCN based Video on Demand (VoD) scenario. The video server maintains a movie library, where movies

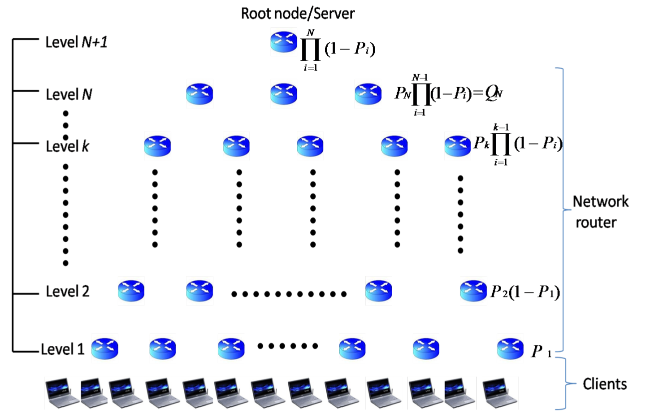


Fig. 1. The layered topology, showing probability Q_k (on the right) of a client traversing k Hops to find content in CCN

(content) are internally subdivided into small pieces (chunks). If a client requests a movie that was not requested by any other client in the network previously, the movie must be retrieved from the server. In this process all the routers which take part to transfer that particular movie to the client will cache the content. For subsequent requests, if the same movie is requested, it will be from the nearest router which already has cached the required content. We define the network model for CCN based on the following assumptions.

The topology has N levels and the root node (server) is on the $N+1th$ level. The server has a fixed storage capacity whereas the network router on a given level k may or may not have a cache capacity depending on the network it belongs to (IP or CCN).

In a practical video streaming application, the probability of finding content on a given tier (level) CCN router will depend on the caching policy and size for a router and the request process. For our analysis we are considering a fixed amount of cache for the network routers and a continuous request process for the content demand. The details of cache policy are out of scope of this report. Q_k is defined as the probability of a client traversing k Hops (levels)to find content (Figure 1). We assume that Q_k is same for all the routers on that level. We also define P_k, the probability of content being present on the k^{th} level. l is the number of nodes at a given level that depends on the tree topology of the network.

The content demand in a VoD application fluctuates during the day [14]. We consider that the network has reached a steady state and is operational for a fixed duration of time (i.e., 3 years in this case). Then the initial demand at a given instance of the demand curve can be modeled as the initial probability p of finding content. p can be used as an indicator of popularity (as content gets more and more popular, it is more likely to be found on the initial level). We define a parameter α which controls variation of popularity across different levels of the network. It can take values between 0 and 1. So we can model the probability of finding the content

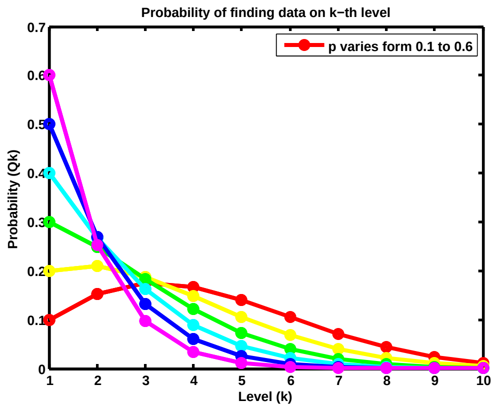


Fig. 2. Trend of Q_k with increasing number of levels

at any level k as,

$$P_k = \begin{cases} 1-(1-p)\exp^{-(k-1)\alpha} & \text{if } k = 1, 2..., N \\ 1 & \text{if } k = N+1 \end{cases}$$

$$Q_k = P_k \prod_{i=1}^{k-1}(1-P_i) \tag{1}$$

where

$$\textstyle\sum_{k=1}^{N+1} Q_k = 1$$

Figure 2 depicts the behavior of Q_k. The expected number of routers (Hops) traversed to retrieve content is then,

$$E(Hops) = \sum_{k=1}^{N+1} kQ_k \tag{2}$$

Where $E(Hops)$ is a function of content popularity and the number of Hops. In case of IP-based network, $P_k = 0$ hence $Q_k = 0$ for $K = 1, 2.., N$ while $P_{N+1} = Q_{N+1} = 1$ so the $E(Hops)$ for IP will always be $N+1$. However for CCN, the expected number of Hops traversed by clients would decrease as the content gets popular. This implies that when the content is popular in the network, the accumulative load of the network decreases. In Section III-C we use this feature of CCN to reduce the energy consumption in the network by operating the network devices at a lower rate, taking into account the fact that the load in the network is decreasing.

B. Energy consumption evaluation

We initialize the analysis by first calculating the emergy and operating energy consumption for different network devices used in our network. We are assuming that our network topology consists of multiple edge routers and a single video server. The total energy consumption of a CCN and IP-based network can be estimated by summing the emergy and operational energy of all the network devices used in that network for a given life cycle (i.e., the time for which network was deployed). It is more common place to find the operational power of network devices instead of operational energy. So we calculate the operational power for the network devices. Now our emergy is in units of Joules so to be consistent in our analysis we can express the quantity as embodied power, which we calculate by dividing emergy by the replacement time of the equipment. We call this as embodied power.

We can establish the energy consumption relations for both IP and CCN based networks as follows,

$$P_{IP} = KM_{IP} + S_m + C_S + O_S + O_{IP}\sum_{k=1}^{N} l_k \tag{3}$$

$$\begin{aligned} P_{CCN} = KM_{CCN} + S_m + C_S + (K-1)C_M \\ + O_S + O_{CCN}\sum_{k=1}^{N} l_k \Phi_k \end{aligned} \tag{4}$$

Where N is the total number of Hops and K is the total number of nodes in the network, l_k is the total number of nodes at a given level. M_{IP} and M_{CCN} are the embodied power for network routers, S_m and O_S are the embodied and operational power consumptions respectively for the server. C_M and C_S are the J/s consumed to power up cache and storage respectively. The network is deployed for the duration of 3 years (this is equivalent to replacement time of the equipment for our analysis). O_{IP} is the operating power consumption for the IP network routers while O_{CCN} is the operating power consumption for a CCN router. We have introduced a power reduction factor Φ in equation 6 in the power relation for CCN. A discussion on Φ is presented in Section III-C. It should be noticed that there is an extra overhead of cache memory power consumption for estimating P_{CCN}.

C. Rate Adaptation

In Section III-A we discussed that the load in CCN will decrease as time passes and content gets popular. We exploit this feature by using routers which are capable of changing their operating rate according to the rate variation on a given link. Hence we assume that the routers in the network are capable of implementing the Adaptive Link Rate (ALR) techniques described by Chamara et al. in [11], [12]. We can define threshold on the rate of our network routers by using link utilization threshold policy as follows.

If R_k is the link rate entering on any level k router in the network and R_{IP}, R_{CCN} are the link rates of the server with and without considering caching in the network respectively in steady state. Then for any given scenario in CCN we can model threshold as the link rate R_k. The first level routers will experience the maximum load so $R_1 = R_{CCN}$. The rate decreases on subsequent levels as the probability of clients traversing k levels to retrieve content decreases according to Q_k, so we define $R_2 = (1 - Q_1)\ R_{CCN}$. Generalizing this we get,

$$R_k = (1 - \sum_{l=1}^{k-1} Q_l) R_{CCN} \quad (5)$$

Such that the operating rate of a CCN router will be tuned according to R_k. Hence we define the energy reduction factor Φ_k for a given level k as,

$$\Phi_k = R_k / R_{IP} \quad (6)$$

Here we are assuming that the energy consumption of a network router varies in proportion to the link rate. In the next section we provide a use case to compare the energy consumption of IP and CCN-based networks.

IV. Performance Evaluation

We consider a simple video on demand service scenario where a single server is providing services to the clients. For our analysis we are using video server from Verivue [15] with (10 TB storage capacity) and Mi10 routers [16] (with an additional 140 GB or 1TB cache). The values which we are considering to calculate the emergy and operating energy are all approximate values. To keep the analysis simple the network topology is considered to be a balanced binary tree, where K is the total number of nodes in the network.

To the best of our knowledge, there is no study available in the literature which provides an exact analysis of the power or energy consumed in manufacturing storage devices, servers and routers. Therefore we estimate these costs from data given in [17], [18], [9], [4] and making use of the available data-sheets for different devices which we are considering in our analysis. It is commonplace to give energy consumption (J) in terms of power (J/s) [4] so we base our analysis on power consumption rather than energy.

A. Embodied power consumption

In year 2000 the emergy of a disk drive of 30GB was 2926 MJ [17]. According to Kryder's law [19], the storage capacity of storage device doubles every 18 months. So by applying Kryder's law we can calculate the amount of storage which can be manufactured using 2926 MJ of energy as follows,

$$2^{\left(\frac{\text{duration in months since year 2000}}{\text{18 months}}\right)} \times \text{Disk capacity in year 2000} \quad (7)$$

$$2^{\left(\frac{12\times 11}{18}\right)} \times 30 \approx 5\text{TB} \quad (8)$$

so the emergy of 10 TB of storage device would be $2926 \times 2 = 5852$ MJ. The size of the cache memory should depend on the scale of the network. We are considering two sizes of cache memory for the CCN routers (i.e., 1TB and 140GB) to compare the difference it makes on overall power consumption of the network. Hence the emergy for 1TB and 140 GB storage is 585MJ, 100MJ respectively. We are assuming that the life cycle for all the devices we are using in our analysis is 3 years. Hence the embodied power for a 10TB, 1TB and 140 GB hard is ≈ 62 J/s, ≈ 6.2 J/s and ≈ 1.2 J/s respectively (embodied power = emergy/life cycle). The server emergy estimated by Seetharam et al. in [9] using the study of E.Williams in [17] is 550 MJ (= ≈ 6 J/s). We are going to use the same estimate for our analysis.

We are considering a simplistic dedicated video streaming scenario so we can assume that the network is populated with same type of routers (Juniper M10i edge routers in this case).

Seetharam et al. estimated the emergy of a router in [9] by scaling the weight of the router relative to the weight of the PC. The weight of a desktop PC varies between 13 to 35lbs [20]. For this analysis we are assuming it to be approximately 25lbs. The weight of a M10i router is 79lbs [16] therefore the emergy of an edge router becomes

$$\frac{79}{25} \times 550 \times 10^6 \approx 1200\text{MJ}, \quad (9)$$

which is equal to 13 J/s (embodied power). The total embodied power for server and network routers is summarized in Table I-A. We are considering the same Mi10 routers for both CCN and IP-based networks. The only difference is that the routers in CCN have a cache memory of 140 GB or 1TB.

Device	**Embodied power (J/s)**
Server (S_m)	68
IP router(M_{IP})	13
CCN router (140 GB cache)(M_{CCN})	15
CCN router (1 TB cache)(M_{CCN})	20

TABLE I
Embodied power consumption for the network devices used in this analysis

The difference between values estimated in Table I-A for server and router's embodied power is of the order of 3 to 6 times. These values are consistent with the values estimated by Raghavan et al. in [4].

In the next section we estimate the power consumed in transmitting a movie through the IP and CCN-based network.

B. Operation power consumption

We are assuming the library size for the server to be $M = 1,000$ movies. Each movie is compressed using DiVX codec and have a size of $Y \approx 700$MB. The server we are using has a storage capacity of 10 TB consisting of an array of ten 1TB devices (e.g., RAID configuration). The maximum downstream rate the server can provide is bottle necked by the read capacity of memory storage (1385 Mbps approx 175 MB/s in this case). The power consumed by 10TB storage is 480 J/s [21] during streaming operation. The operating power consumption for 140 GB and 1TB cache memory is 7.22 J/s and 48 J/s respectively [21].

The total energy spent by a server's chip-set during video streaming can be calculated by following the model adopted in [9]. For a typical server the operating power of a multi-media streaming application is 251 J/s. The chip-set of edge routers we are using for this analysis (i.e., M10i) operate at 116 J/s.

For IP-based network the router operating power is only the power consumed in operating the M10i routers but for CCN the router operating power also includes power consumed by the cache memory during its operation. Table II-B show the total power (chip-set + storage) for operation of server and routers.

Device	**Operating Power (J/s)**
Server (O_S)	731
IP router(O_{IP})	116
CCN router (140GB cache)(O_{CCN})	124
CCN router (1TB cache)(O_{CCN})	164

TABLE II
OPERATING POWER OF THE NETWORK DEVICES USED IN THIS ANALYSIS

We should also consider the energy required to power up the cache memory at the network routers and the memory storage at server. These values can be extracted from the available data-sheets of the memory devices used [21]. The values are presented in Table III-B.

Power required to power up memory	Value (J/s)
Router cache memory (C_M) 140 GB	0.053
Router cache memory (C_M) 1 TB	2
Server memory (C_S)	20

TABLE III
POWER REQUIRED TO POWER UP THE STORAGE AND CACHE MEMORY

V. RESULTS

The power consumption values calculated in Section IV are used to estimate the power consumption of IP and CCN-based networks using equations 3 and 4 respectively. We have implemented these equations in MATLAB to perform the comparative study between CCN and IP-based Network. Figures 3 and 4 show the comparison of power consumption between IP and CCN-based networks. The value of p is 0.1 and $alpha$ is 0.2. The network is considered to be running for the duration of 3 years. We are analyzing this system for a worst case scenario (i.e., peak load and peak power ratings).

From Figure 3(a) and 3(c) we can observe that CCN performs better in terms of power consumption as the network grows larger. The cache introduces an extra power overhead in the network due to its embodied power consumption. Figure 3(b) and 3(d) show that in worst case scenario where no rate adaptation technique is implemented in the network routers, IP out performs CCN. Here we are assuming that CCN routers would be operating at the same rate as IP routers. This would not be the case in a practical CCN implementation, even if rate adaptive routers are not used. The CCN network would intrinsically work on a lower rate due to caching of content in the network. In that situation we can deploy CCN using routers which operate at a lower rate.

Figure 4(a) and 4(c) show that the power consumption of CCN-based network decreases as the popularity of the content increases. It can be observed from Figures 4(b) and 4(d) that popularity of content has no effect on the power consumption of a CCN if rate adaptation is not used. Here again the

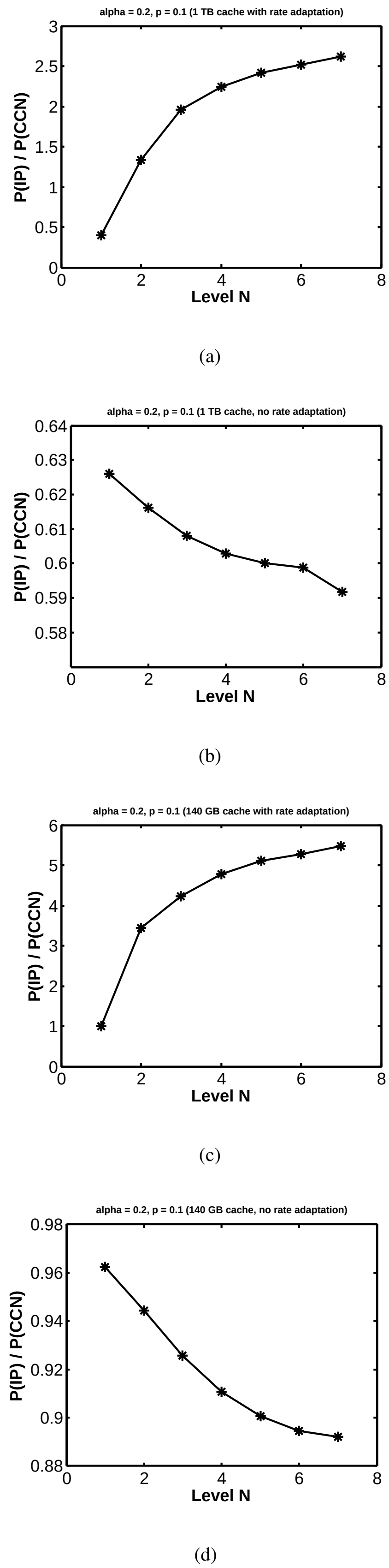
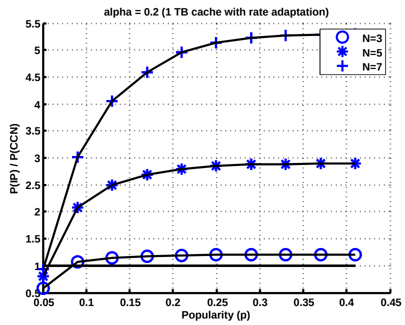
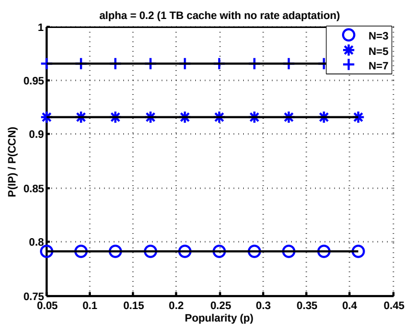


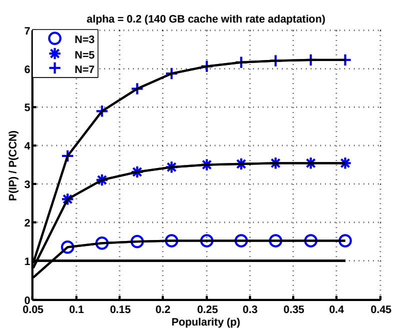
Fig. 3. Power Ratio of IP compared to CCN-based networks: (a),(b) show the power ratio (with and without rate adaptation respectively) versus the number of levels of the network with 1 TB cache, (c),(d) show the same analysis for 140 GB cache



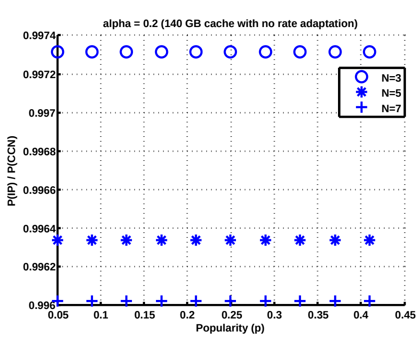
(a)



(b)



(c)



(d)

Fig. 4. Power Ratio of IP compared to CCN-based network: (a), (b) show the power ratio (with and without rate adaptation respectively) versus the content popularity in the network with 1 TB cache, (c), (d) show the same analysis for 140 GB cache

underlying assumption is that IP and CCN routers operate at the same rate. The argument presented in the paragraph above will also be valid here. Another interesting observation we can make from Figure 4(d) is that when the cache memory is low in a CCN router, the power overhead is small and the energy ratio between IP and CCN is nearly 1. This implies that if the cache memory is designed optimally for the CCN routers then even in the worst case situation IP would only perform marginally better than CCN.

VI. Conclusion

We have presented a comparative study of energy consumption for CCN and IP-based networks in a VoD scenario. Although our network model is based on simplistic assumptions but it provides an intuitive understanding of content dissemination in CCN. We have conducted an energy analysis by taking into account the power consumption (energy/sec) of different network devices. Our results show that a CCN outperforms IP-based network implementation in terms of power consumption if network is large and content is popular.

In future our goal is to improve the simplistic network model presented here and compare it with other CCN models. We will also try to define a mechanism to optimally calculating the cache size for CCN routers.

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