Energy-Efficient Distributed In-Network Caching for Content-Centric Networks

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***Abstract*—Due to the in-network caching capability, Content-Centric Networking (CCN) has emerged as one of the most promising architectures for the diffusion of contents over the Internet. In this paper, we propose an energy-efficient distributed in-network caching scheme for CCN. In the proposed scheme, each content router only needs locally available information to make caching decisions considering both caching energy consumption and transport energy consumption. We formulate the energy-efficient distributed in-network caching problem as a non-cooperative game. Through rigorous mathematical theorems, we prove that Pure strategy Nash equilibria exist in the distributed solution, and it always has a strategy profile that implements the socially optimal configuration, even if the routers are self-interested in nature. Simulation results reveal that the proposed scheme is competitive to the centralized scheme, and has superior performance compared to the other widely used schemes in CCN.**

***Index Terms*—In-network caching, content-centric networking, energy efficiency, non-cooperative game**

I. Introduction

With the explosive growth of the Internet traffic caused by sharing user generated data (e.g., YouTube) and delivering multi-media content (e.g., Netflix), Internet communication pays more attention to the content itself rather than where it is physically located [1], [2]. However, the current Internet, originally conceived to enable communication between machines, lacks natural support for content distribution. This fundamental mismatch has a significant impact on the network performance in terms of end user quality of experience, bandwidth costs, delay, and energy use [3], [4].

Initial attempts to accommodate content distribution within the Internet infrastructure have resulted in a plethora of application-specific solutions, e.g., Content Delivery Networks (CDNs) and Peer-to-Peer (P2P) networks, which have bulit-in large-scale and distributed caching mechanisms. However, content caching is only deployed as an overlay service rather than an inherent network capability. Due to the lack of storage capability at individual routers, these caching mechanisms lead to suboptimal utilization of network resources [5].

Recently, as a potential solution to these limitations, Content-Centric Networking (CCN) [3] has emerged as one of the most promising architectures for the diffusion of contents over the Internet. A major feature of this novel networking paradigm is in-network caching [6]–[8]. In CCN, each content router has caching capability, which can cache content objects to shorten the distance of user requests.

Although some excellent works have been done on CCN, most of them focus on the performance improvement of network resource utilization [4]. Consequently, the energy consumption aspect in this setting is largely ignored [9]. However, the increasingly rigid environmental standards and rapidly rising energy costs have led to an emerging trend of addressing "energy efficiency" issues [10]–[13]. Indeed, the energy consumption of the Internet is estimated to account for up to 10% worldwide energy consumption and keeps constantly increasing [14]. The authors of [15], [16] make fine attempts in considering energy efficiency of CCN. However, the schemes proposed in [15], [16] are centralized schemes to minimize the global network energy, which may not be practical to be implemented in realistic networks due to the distributed architecture of the Internet [17]. Particularly, in multiple Internet service providers (ISPs) environment, it is difficult to have a centralized administration to coordinate content routers that belong to different ISPs.

In this paper, we propose an energy-efficient distributed in-network caching scheme for CCN. In the proposed scheme, each content router only needs locally available information to make caching decisions considering both caching energy consumption and transport energy consumption. We formulate the energy-efficient distributed in-network caching problem as a non-cooperative game [18]. Through rigorous mathematical theorems, we prove that Pure strategy Nash equilibria exist in the distributed solution, and it always has a strategy profile that implements the socially optimal configuration, even if the routers are self-interested in nature. We evaluate the proposed distributed scheme in heterogeneous network conditions and compare it with a centralized scheme and other common techniques in CCN, such as Leave Copy Everywhere (LCE), FIX(P), Random Caching (RND) and Unique Caching (UniCache) [19] using Inet [20] network topology generator. Simulation results reveal that the proposed scheme is competitive to the

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centralized scheme, and has superior performance compared to the other widely used schemes in CCN. Besides, it exhibits a fast convergence speed when the capacity of content routers varies.

The rest of this paper is organized as follows. In Section II, the system model is given. In Section III, the problem to resolve is formulated, and the centralized solution is presented. In Section IV, the distributed solution based on non-cooperative game is presented. Simulation results are presented and discussed in Section V. Finally, we conclude this study in Section VI.

II. System Model

In this section, we briefly present an overview of CCN. Then, the network model and energy consumption model are described.

A. Overview of Content-Centric Networking

CCN is a receiver-driven, data-centric communication protocol. Communication in CCN is performed using two distinct types of packets: *Interest Packets* and *Data Packets*. Both types of packets carry a name, which uniquely identifies a piece of data. Besides, to receive data, each CCN content router maintains three major data structures: a *Content Store* (CS) for temporary caching of received data packets, a *Pending Interest Table* (PIT) to contain the name of the interest packet and a set of interfaces from which the matching interests have been received, and a *Forwarding Information Base* (FIB) to forward the interest.

B. Network Model

We briefly summarize the notations of the key parameters and their values used in the simulations in Table I.

TABLE I
Notations and Values of the Key Parameters

Symbols	Notations	Values
N	Number of network nodes	64
M	Number of different network contents	100
t	Time duration	3600 seconds
C_i	Maximum cache size at content router i	Multiple values
d_{ij}	Hop distance between content router i and j	Multiple values
q_i^k	Request rate for object O_k at node i	Multiple values
s^k	Size of the content object O_k	Multiple values
p_d^r	Power density of a core router	1.7×10^{-8} J/bit
p_d^{wdm}	Power density of a WDM link	5×10^{-9} J/bit
p_d^{roadm}	Power density of a ROADM	1.95×10^{-11} J/bit
w_{ca}	Power of storage (hard disk)	Multiple values

We model the CCN network as a connected graph $G = (V, E)$, where $V = (V_1, V_2, .., V_N)$ is the set of content routers in the network, and $E \subseteq V \times V$ is the set of network bidirectional links. Let $O = (O_1, O_2, .., O_M)$ be the set of content objects that can be available in the network. All of the objects are initially distributed in the network servers, which are directly connected to edge content routers. For the sake of readability, the term "content router" and "node" will be used interchangeably here. Let $U \subseteq V$ be the set of end nodes. End nodes are responsible for collecting the interest packets for different content objects from their users and spreading them to the network along the selected routers. Each node $V_i \in V$ is associated with a cache, which can store up to C_i content items, such that the content forwarded by the node can also be stored locally.

C. Energy Consumption Model

We consider a case that CCN routers carry out the tasks of content servers [4]. In this case, the content servers holding the original contents are infrequently accessed, so we do not consider their energy consumption. As such, the total energy consumed by CCN consists of two major parts: caching energy consumption E^{ca} and transport energy consumption E^{tr}.

1) Caching Energy Consumption, E^{ca}: We use an energy-proportional model [21]. If node i caches content object O_k within an observed time interval t, the energy consumed by caching s^k bits is given by [15], [16]

$$E_{ik}^{ca} = w_{ca} s^k t \tag{1}$$

where w_{ca} is the power efficiency of caching. The value of w_{ca} strongly depends on the caching hardware technology.

2) Transport Energy Consumption, E^{tr}: The transport energy consumption mainly consists of the energy consumption at routers and energy consumption along the links. We assume that a user acquires any one content from a single content router, so the energy consumed by node i to request content object O_k from node j can be expressed by:

$$E_{ijk}^{tr} = q_i^k s^k \left[(1 + d_{ij})(p_d^r + p_d^{roadm}) + d_{ij} p_d^{wdm}\right] \tag{2}$$

III. Centralized Solution to In-Network Caching for CCN

Before we present the distributed in-network caching scheme for CCN, we first formulate it as a centralized optimization problem. In this paper, our objective is to achieve optimal energy efficiency by addressing the question of how each content router with limited caching capacity caches contents in CCN. The energy-efficient in-network caching problem can be formulated as an integer linear problem (ILP) as follows:

$$\begin{aligned}
\min_{x,y}: \quad & \sum_{i=1}^{N}\sum_{k=1}^{M}\left(E_{ik}^{ca}x_{ik}+\sum_{j=1}^{N}E_{ijk}^{tr}y_{ijk}\right)\\
s.t.: \quad & \sum_{j=1}^{N}y_{ijk}=1, \forall i,k\\
& y_{ijk}\le x_{jk}, \forall i,j,k\\
& \sum_{k=1}^{M}s^{k}x_{ik}\le C_i, \forall i\\
& y_{ijk}\in\{0,1\}, x_{ik}\in\{0,1\}, \forall i,j,k
\end{aligned} \tag{3}$$

where x_{ik} takes the value of 1 if node i caches a copy of element k, and 0 otherwise. y_{ijk} takes the value of 1 if node i downloads a copy of content object k from node j, and 0 otherwise. In this ILP, the objective function consists of two terms for the transport and caching energy, respectively. The first constraint specifies that each content router i downloads content object O_k from only one content router. The second constraint specifies that content router i can download object O_k from content router j only when that content element is located there. Finally, the third constraint specifies that the total size of the elements located on content router i should not exceed its maximum cache size.

Although we can use the above ILP model to achieve the globally minimal energy consumption, in general, centralized solution may be impractical due to the distributed architecture of CCN. Note that the number of variables and constraints of the ILP formulation grows approximately as N^2M. Therefore, in the following section, we present a fully distributed solution, that allows each node to make caching decisions without requiring global knowledge of the request arrival process and network resources.

IV. Non-cooperative Game Solution to In-Network Caching for CCN

In this section, we take a game-theoretic approach with a payment mechanism to analyze the in-network caching problem among selfish nodes in the network. We first present the utility model of the non-cooperative game, which considers the cache size constraint. Then, we analyze the utility model, and prove the existence of Nash equilibria in the the non-cooperative game.

A. Utility Model

Let $G=(\mathcal{N},\varsigma,\chi)$ denote the non-cooperative game, where $\mathcal{N}=\{1,2,...,N\}$ is the set of players, ς is the set of strategy profiles, and χ is the utility function. To formulate the energy saving problem as a non-cooperative game, we need to define a utility function suitable for energy-efficient content delivery. The utility function needs to take into account the incentive offered by other nodes, in addition to the transport energy costs and caching energy costs of the centralized solution. In the game, we assume that each node's strategy is rational, that is, each node decides to cache or not independently that minimizes its current energy cost. So we can look at the replication of each object as a pure strategy. The goal of the game is to find the optimal caching configurations when each node optimizes its energy utility functions locally.

Definition 1 (feasible strategies): A node i's strategy is termed feasible φ_i, when the storage constraint is met before a decision to replicate an object O_k can be undertaken.

So φ_i is the set of feasible strategies for a node i. Of all of the feasible strategies, let $\varsigma_i\in\varphi_i$ be a strategy chosen by node i. Here ς_i is specified by a tuple $(I_i,v_i,b_i,t_i,R_i)\in\{N,N,R_+,R_+,R_+\}$. I_i is the corresponding indicator variable, that is, I_i equals 1 if i replicates the object O_k, and 0 otherwise (Note that I_i only focuses on a specific object O_k. Therefore, it is not necessary to write I_i as I_{ik}.). v_i specifies the player to whom i makes a bid, $b_i\ge 0$ is the value of the bid, and $t_i\ge 0$ denotes a threshold for payments beyond which i will replicate the object. In addition, R_i is used to denote the total amount of bids received by a node i and defined as

$$R_i=\sum_{j:v_j=i}b_j \tag{4}$$

A node i replicates the object if and only if $R_i\ge t_i$. We make the rule that if a node i makes a bid to another node j and j replicates the object, then i must pay j the amount b_i. If j does not replicate the object, i does not pay j.

Definition 2 (strategy profile): A strategy profile $\varsigma=(\varsigma_1,...,\varsigma_N)$ is a set of strategies. An element in this set corresponds to the strategy of an individual node that fully specifies all of its actions. A strategy profile must include one and only one strategy for every node.

For convenience, we can also write ς as $(\varsigma_i,\varsigma_{-i})$, where ς_i is the strategy of node i, and ς_{-i} is the set of strategies of all other nodes in the game excluding node i. Given ς, one can easily find out which nodes have opted to replicate O_k.

Given a strategy profile, the outcome of the game is the set of tuples $\{(I_i,v_i,b_i,t_i,R_i)\}$. For O_k, the node chooses a strategy $\varsigma_i\in\varphi_i$ that describes its desire to replicate or otherwise. Thus, given a strategy profile ς, we say that a node i incurs an energy cost $\chi_i(\varsigma)$ if it considers replicating object O_k. It is the sum of its caching energy cost, transport energy cost, and net payment, and defined as

$$\chi_i(\varsigma)=E_{ik}^{ca}I_i+E_{iv_ik}^{tr}I_{v_i}+b_iI_{v_i}-R_iI_i \tag{5}$$

B. Analysis

In this subsection, we analyze the energy utility model to obtain stable solutions called Nash equilibria. When each node i plays ς_i, then node i incurs a cost $\chi_i(\varsigma)=$

Algorithm 1 Initialization for the Non-cooperative Game

L_1^k = a set of source servers caching content O_k
L_2^k = a set of content routers (nodes) caching content O_k
L_3^i = a set of contents cached on node i
for each node i in N **do**
  $b_i = 0$, $t_i = E_{ik}^{ca}$, $L_3^i = \phi$
end for
for each content O_k in M **do**
  $L_2^k = \phi$
end for

$\chi_i(\varsigma_1, ..., \varsigma_N)$. Formally, the non-cooperative game G is expressed as

$$\min_{\varsigma_i} \chi_i(\varsigma_i, \varsigma_{-i}), \forall i \in N \quad (6)$$

Definition 3 (pure Nash equilibrium): A situation in a non-cooperative game in which nodes play using a set of deterministic strategies whereby no node can improve its benefit by changing its strategy unilaterally.

Lemma 1: A strategy profile ς^* is a pure Nash equilibrium of non-cooperative game if for any deviation, ς_i by a node i is not beneficial, that is, $\chi_i(\varsigma_i, \varsigma_{-i}^*) \geq \chi_i(\varsigma_i^*, \varsigma_{-i}^*)$.

The Nash equilibrium concept offers a predictable, stable outcome of a game where multiple nodes with conflicting interests compete through self-optimization and reach a point where no player wishes to deviate.

Lemma 2 (combining pure Nash equilibria): If two games are known to have a pure Nash equilibrium, then their union is also guaranteed to have a pure Nash equilibrium.

Thus, if we are able to prove that a given ς conforms to a pure Nash equilibrium, then $\cup\varsigma_i$ also conforms to a pure Nash equilibrium. Conversely, if $\chi(\varsigma)$ is the energy cost function associated with ς, then the $\sum \chi(\varsigma_i)$ over all M objects is the cost associated with $\cup\varsigma_i$.

1) Existence of Pure Nash Equilibrium: In the formulated non-cooperative game, there are no cycles of actions, because we analyze the game within the time interval t. In principle, we can start with a random configuration and let this configuration evolve as each node alters its strategy and attempts to minimize its energy cost. A pure strategy Nash equilibrium is reached when no node can benefit by unilaterally changing its strategy.

In the game, we first initialize a set of servers in network to cache the content objects requested by end users, and there are no contents cached on any content router. The details are shown in Algorithm 1. After the initialization, each node runs the decision-making processes described in Algorithm 2. Each player in this procedure greedily chooses between replication and accessing a remote replica of content O_k. In the procedure, each node increases its threshold value by $incr$ if it does not replicate the content O_k. By doing like this, the energy cost of replicating content O_k is shared fairly among the nodes that access a replica of content O_k from a node that does cache.

Algorithm 2 Decision-making Processes on Content O_k for Node i along the Routing Path

if node i caches content O_k **then**
  $M_i^k = \left\{ j : E_{jik}^{tr} < \min_{l \in L_1^k \cup L_2^k} E_{jlk}^{tr} \right\}$
  if $M_i^k \neq \phi$ **then**
    for each node j in M_i^k **do**
      $b_j = \max \left\{ \left(E_{ik}^{ca} + \sum_{l \in M_i^k} E_{lik}^{tr} \right) / |M_i^k| - E_{jik}^{tr}, 0 \right\}$
    end for
    $R_i = \sum_{j \in M_i^k} b_j$, $cost_1^k = E_{ik}^{ca} - R_i$
  end if
else
  $cost_2^k = \min \left\{ \min_{j \in L_1^k} E_{ijk}^{tr}, \min_{j \in L_2^k} \left(t_j - R_j + E_{ijk}^{tr} \right) \right\}$
end if
$costmin = min \left\{ cost_1^k, cost_2^k \right\}$

if $costmin == cost_1^k$ **then**
  if cache is not full **then**
    $t_i = R_i$, $L_2^k = L_2^k \cup \{i\}$
  else
    if $cost_1^k < \max_{k' \in L_3^i} cost_1^{k'}$ **then**
      replace content k' with k
      $L_3^i = L_3^i \cup \{k\} - \{k'\}$, $L_2^k = L_2^k \cup \{i\}$, $L_2^{k'} = L_2^{k'} - \{i\}$
    end if
  end if
else
  $t_i = R_i + incr$
  if $cost_2^k == \min_{j \in L_1^k} E_{ijk}^{tr}$ **then**
    $b_i = 0$
  else
    $v_i = \arg\min_{j \in L_2^k} \left\{ t_j - R_j + E_{ijk}^{tr} \right\}$, $b_i = t_{v_i} - R_{v_i}$
  end if
end if

Because there are no cycles of actions in the game, we know that the procedure in Algorithm 2 can converge to a stable status where no player can improve its energy benefit by changing its strategy unilaterally. Therefore, based on Lemma 2, we know that the pure Nash equilibria exist in the non-cooperative game.

2) Optimistic Price of Anarchy: In this subsection, we analyze the best Nash equilibrium of the non-cooperative game, called optimistic price of anarchy (OPoA). Next we prove that indeed the game always has a strategy profile that implements the socially optimal configuration as a Nash equilibrium.

Let N_o be the set of nodes that replicate the object O_k and $N_c = N - N_o$ be the rest of the nodes. Also, for each node i in N_o, let Q_i denote the set of nodes that access the object O_k from i, not including i itself. In the optimal configuration, $E_{jik}^{tr} \leq E_{jk}^{ca}$ for all j in Q_i. To find a set of payments and thresholds that makes this caching configuration implementable, we define

$$\delta_j = min \left\{ E_{jk}^{ca}, min_{l \in N_o - \{i\}} E_{jlk}^{tr} \right\} - E_{jik}^{tr} \quad (7)$$

where δ_j is the difference between j's energy for accessing the replica at i and j's next best option among replicating the object and accessing some replica other than i. It is clear that $\delta_j \geq 0$.

We set bids as follows. For each i in N_o, $b_i = 0$ and for each j in Q_i, j bids to i (i.e., $v_j = i$) the amount:

$$b_j = max\left\{0, \delta_j - \epsilon_i/\left(1 + |Q_i|\right)\right\}, j \in Q_i \tag{8}$$

where $\epsilon_i = \sum_{j \in Q_i} \delta_j - E_{ik}^{ca} + E_{il_ik}^{tr} \geq 0$, l_i is the nearest node to i in N_o, and $|Qi|$ is the cardinality of Q_i. For the thresholds, we have:

$$t_i = \begin{cases} E_{ik}^{ca} & \text{if } i \in N_c \\ \sum_{j \in Q_i} b_j & \text{if } i \in N_o \end{cases} \tag{9}$$

This fully specifies the strategy profile of the nodes, and it is easy to see that the outcome is indeed the socially optimal configuration.

Next, we verify that the above strategies constitute a Nash equilibrium. Having set t_i to E_{ik}^{ca} for node $i \in N_c$ means that any node in N is at least as well off lowering its threshold and replicating as bidding E_{ik}^{ca} to some node in N_c to make it replicate. To ensure that each node $i \in N_o$ does not deviate, we require that if l_i is the nearest node to $i \in N_o$, then $\sum_{j \in Q_i} b_j$ is at least $E_{ik}^{ca} - E_{il_ik}^{tr}$. Otherwise, node i will raise t_i above $\sum_{j \in Q_i} b_j$ so that it does not replicate content k and instead accesses the replica at l_i. We can easily check that

$$\begin{aligned} \sum_{j \in Q_i} b_j &\geq \sum_{j \in Q_i} \delta_j - |Q_i|\epsilon_i/\left(|Q_i| + 1\right) \\ &= E_{ik}^{ca} - E_{il_ik}^{tr} + \epsilon_i/\left(|Q_i| + 1\right) \geq E_{ik}^{ca} - E_{il_ik}^{tr} \end{aligned} \tag{10}$$

Therefore, for content O_k, each node $i \in N_o$ does not have incentive to change t_i since i loses its payments received or there is no change, and i does not have incentive to b_i since it replicates the object. Each node $j \in N_c$ has no incentive to change t_j since changing t_j does not reduce its cost. It also does not have incentive to reduce b_j since the node which j accesses does not replicate and j has to replicate the object or to access the next closest replica, which costs at least the same from the definition of b_j. No player has incentive to deviate, so this strategy profile on content O_k is a Nash equilibrium. Using Lemma 2, we know that the strategy profile is the socially optimal pure Nash equilibrium of the non-cooperative game.

V. Simulation Results and Discussions

In this section, we use computer simulations to evaluate the performance of the energy-efficient distributed in-network caching scheme. In the simulation, there are 100 different contents, and the total number of content objects is 2×10^6 in the network. We assume each object has the same size and the content popularity follows the Zipf distribution (the skewness factor $\alpha = 0.8$) [16]. Besides, we abstract the cache size for each content router as the proportion relative to the total amount of different contents in the network, which varies from 1% to 10%. The simulation evaluation is carried out in the Power-Law topology generated using Inet topology generator [20]. The topology includes 64 content routers, among which there are 40 edge content routers directly connected to end users. The widely used caching decision policies in CCN, such as Leave Copy Everywhere (LCE), FIX(P), Random Caching (RND) and Unique Caching (UniCache) [19] are used as comparative objects, and all of them adopt the popular Least Recently Used (LRU) as their cache replacement policy. Given the objective of minimizing the energy consumption in CCN, we mainly consider energy saving rate (ESR) in the simulations, which is the ratio of the saved energy by in-network caching policies to the total energy consumption incurred by LCE.

Fig. 1 shows the ESR of each solution when the cache size varies. As the cache size increases, the increasing caching energy can achieve less transport energy by effectively reducing the distances to content. Before the cache size increases to 7%, the ESR of each policy decreases gradually because the energy cost of LCE declines the fastest. But the gap between the centralized policy and distributed policy is widening. The reason is that the node in the distributed policy does not collect enough payment caused by nodes' selfishness to compensate for the cost of replicating the content, which is called replica under-supply problem in this paper. After that, with a larger cache size, the energy cost of centralized and distributed solutions cannot be improved because they have made a trade-off between the caching energy consumption and transport energy consumption. However, the energy cost of the other polices is increasing because they cache more replicas. We can observe that, when the cache size is equal or greater than 7%, the gap between the distributed policy and LCE is increasing and that between the centralized policy and distributed policy is narrowing gradually, and the gaps between other solutions and LCE almost remain the same.

Fig. 2 shows the convergence performance of the distributed solution when the cache size varies. The energy of each slot is calculated based on a simple assumption that the size of each content object is 1 bit. From Fig. 2, we can observe tha the proposed distributed algorithm on the whole has a fast convergence speed and the cache size has some effects on the convergence of the distributed algorithm. The larger the cache size is, the longer the convergence time of the distributed algorithm is. The reason is that, with a larger cache size, the contents in content routers need to be replaced more frequently to achieve a stable status.

VI. Conclusions

In this paper, we have studied the issues of content placement and replacement problems for CCN to improve

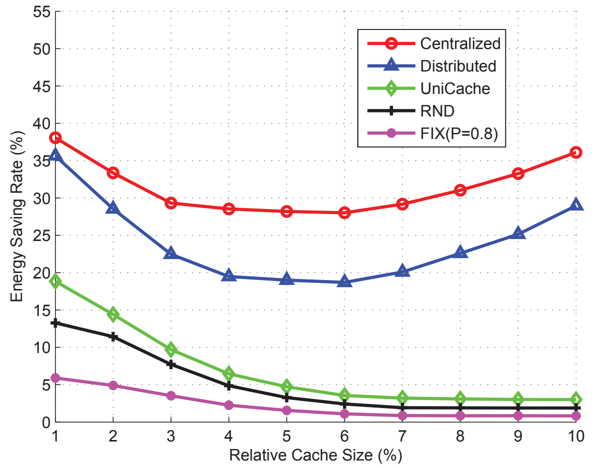

Fig. 1. Energy saving rate versus cache size in the Power-Law topology ($\alpha = 0.8$, and $w_{ca} = 2.5 \times 10^{-9}$ Watt/bit).

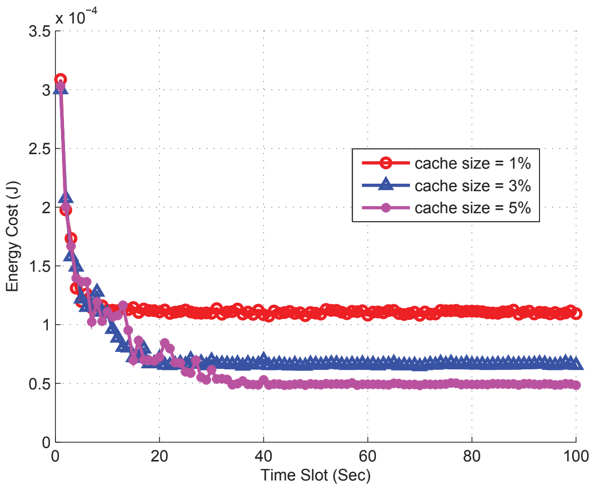

Fig. 2. Energy saving rate versus time slot in the Power-Law topology ($cache\ size = [1\%\ 3\%\ 5\%]$, and $\alpha = 0.8$, $w_{ca} = 2.5 \times 10^{-9}$ Watt/bit).

energy efficiency. We have formulated the content placement problem as a non-cooperative game. We proved the existence of pure Nash equilibria in the non-cooperative game, and with a payment scheme the game can always implement the social optimum in the best case. Simulation results have been presented to demonstrate that the distributed solution is competitive with the centralized solution, and improves the performance significantly compared with other popular caching polices in CCN. Besides, when the capacity of content routers varies, our distributed solution can converge to a stable status at a fast speed.

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