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A collaborative caching over PLC for remote areas

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***Abstract*—Power line communication (PLC) technology has emerged to foster ease of reach for broadband access network in remote or developing areas at lower costs by making use of existing wired power infrastructure for electricity distribution. The increase in data demand, pushed by the popularity of communication services, poses an overwhelming burden on the underlying PLC technology, especially for backhaul links. To confront this issue, edge server deployed at the access network improves data processing and reduces network delays and also helps better provisioning of resources which are crucial for PLC networks. Moreover, data caching at specialized nodes such as edge servers brings forth efficient retrieving, storing and processing of data.**

In this work, we propose a distributed data caching scenario jointly based on edge server (ES) and edge devices (EDs) that are equipped with caching facility and are communicating via PLC in a remote area. We develop a framework to test the mutual collaboration between ES and EDs for content fetching to minimize the use of cloud resources and relieve the load on possibly congested PLC backhaul links. Results reveal that a collaborative caching would boost effective utilization of low bandwidth PLC links and the shift of most popular contents at user premises is crucial to improve socio-economic growth and digital learning platforms for unconnected part of the world.

***Index Terms*—PLC, 6G networks, Edge caching, Remote Areas**

I. INTRODUCTION

In 2018, 55% of total world's population comprised people living in urban areas, whereas, only 3.9 billion people are connected through internet leaving 3.7 billion unconnected [1]. Many from those unconnected belong to remote and rural areas where this digital segregation is effecting information transfer which could otherwise bring prospects of living in the society. The conceptual design of 6G is already highlighting this issue and incorporating it as an objective to address the peculiarities of remote and rural areas by providing connectivity and bridging the digital divide [2], [3].

Power line communication (PLC) technology allows a network deployment over an existing power line infrastructure by enabling use of power cables to support data transmission [4]. Thus, PLC networks with broadband over power line (BPL) technology can be used as a cost effective connectivity solution [5] for non supplied rural and remote areas, which lack wireless and mobile coverage at its premises due to economic and technical challenges. Nevertheless, PLC has its own limitations in terms of available bandwidth, where the users have to share the available capacity and hence the link may remain congested for downloading heavy content. Moreover the global broadband use cases are video downloading and fast access to the websites [6] that require higher data rates. As a result, PLC networks can cause very large delays for downloading a video content even when the cloud services may not be directly utilized [7].

Edge computing has appeared to efficiently manage user demands at its premises and reduce the processing and application overload on the cloud [8]. Furthermore, data storing at the edge results in shorter delays as services remain in proximity of users and this enables effective retrieving, distributing and processing of data. For larger content requests, such as a video content, data has to traverse over the Internet as it may be located in different domains. A caching facility at the edge server is the paradigm to boost fast delivery of contents and reduce the retrieval latency [9]. Edge caching further impacts in reduction of carbon emissions by reducing the amount of overall content needed to traverse in the network which in turn minimizes the network energy consumption and contribute for green and sustainable networking goal [10]–[12]. Therefore, an edge server with caching facility can reduce the network load and enhance the effective bandwidth utilization by contracting the delays associated with content downloading. This could be helpful for the remote and rural areas network, where the provided connectivity is limited for back-end network and front-end network service requirements are met through a low capacity network i.e., a PLC network.

Hence, amalgamating two technologies, PLC network for broadband services and caching at the edge on specialized nodes would be a promising solution for network provisioning in remote areas with effective content distribution. Therefore, in this paper, we propose a collaborative content caching over a low-capacity PLC network, to provide contents in remote areas. The environment consists of an edge server (ES) deployed at the premises of distribution network and edge devices (EDs) or user nodes that are connected through BPL. Both ES and EDs are equipped with a caching facility, where ES has a larger cache to store the most popular contents, whereas a relatively much smaller cache facility is also present at each ED to support a collaborative sharing of contents between ES and EDs. Our major contributions are:

- We develop a simple formulation to estimate the average time for downloading a content stored at ES and EDs.
- We observe the impact of popular content caching and collaborative sharing among edge server and user premises.
- We analyse the usefulness of our strategy in the realm of mobile communication network for remote areas, when

cloud resources cannot be utilized for video on demand traffic and are primarily reserved for the high priority services.

The rest of the paper is organized as follows, In Section III, an architecture of collaborative caching over PLC network is described. Then Section IV presents the system model and a derivation of the average download time for content under the proposed method. Section V discusses about the considered scenarios for proposed collaborative caching. The simulation results are then presented in Section VI and a conclusion is presented in Section VII

II. BACKGROUND & RELATED WORK

PLC has emerged as a reliable solution for information transfer and has significant advantages over wireless communication in smart grid systems and other key areas due to its easy installation and maintenance. With progressive work in PLC domain, the achievable data rates have also been improved to $1\text{Gb}/s$ [13] and hence the technology can foster the demand of internet connectivity in the hard to reach areas or where the infrastructure is not much developed. Rapid growth in data traffic however burdens the PLC network that is used to connect the end users with central server and constrains the overall system performance. Moreover, the technology also experiences attenuation and losses due to high frequency transmission lines and collectively impose challenges on reliable transmission of data for long distance communication over PLC [14]. Edge caching technology offloads the back-haul and place the data near user premises to minimize the network traffic and optimize the use of overall network resources.

Content caching has been widely investigated for wireless technology for optimizing the transmission delays, network resource provisioning and improving the other system performance parameters. Edge and cloud coordinated caching strategy is studied to optimize the cache and core network resources for wireless communication network [15]. Among several cache placement policies, [16] proposed a popularity predicting caching technique to address backhaul bottleneck problem in cellular networks. They used raw data to train the prediction model to forsee the popularity and suggests a caching strategy aiming to minimize traffic load in backhaul network. However, network aspects of wireless technology are different from PLC communication. [17] contributed by suggesting a cache enabled multiple-input multiple-output (MIMO) PLC network. They cached popular content closer to users and proposed a framework to minimize average downloading price for each user. Edge computing over the PLC network has been investigated in the Internet of Things (IoTs) scenario to reduce redundant data transmission between end users and the cloud [18].

In our study, we propose a collaborative caching approach to reduce the load on backhaul cloud link and increase the utilization of PLC link capacity. The performance is compared using different scenarios and presented in Section VI

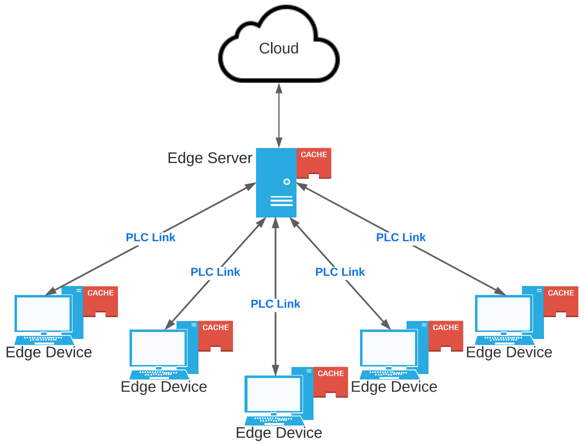


Fig. 1: The proposed collaborative caching network over PLC network.

III. COLLABORATIVE CACHING OVER PLC NETWORK

In this section we describe the system architecture and the collaborative caching approach.

A. System Architecture

The existing grid infrastructure can support PLC over the low voltage (LV) and medium voltage (MV) power lines for transmission of data, which could be exploited with PLC protocols to establish a connection between in-home users and the PLC access network [19]. Thus, existing resources can be used to bring the connectivity to remote areas and reach digital inclusion by connecting the unconnected part of the world through minimum capital investment.

In the proposed scenario a caching facility is combined with the broadband PLC network to meet user demand and address limited data rate challenges related to PLC technology. As shown in Fig. 1, at the access network, an ES equipped with caching is deployed to manage the local EDs or user nodes that are connected through the PLC network. EDs are equipped with caches as well. At the central node (ES), high demand contents (i.e., those with high popularity index) are stored, whereas, a comparatively less popular contents are cached at the user nodes (EDs) to support collaborative caching.

When a user requests content that is not available at its premises, a data request is generated towards the ES. If the ES fails to find the content through its local cache, two alternatives are possible. First, the content can be retrieved from the cloud; second, the data can be retrieved from a cache in an ED, according to a *cooperative caching* scheme. In this latter case, the ES performs a lookup into a database, where it maintains the list of contents stored in each ED and then the required content is retrieved at central node (ES) from the ED that has the content. Finally the data is transferred to the ED that has performed the request. This reduces the load on the backbone network and link that connects the ES with the cloud. Thus, the ES and EDs will perform a mutual collaboration to utilize the available caching resources at maximum thereby restraining use of the link towards the cloud that is the most expensive link to fetch the content from. In case none of the EDs has the content, it can be retrieved from the cloud, provided that some bandwidth is available and the link is not too congested.

B. Distribution of Contents

As is usually done in the literature, the content popularity is defined according to Zipf distribution with a skewness parameter α [20]; the Zipf distribution well represent the fact that a few contents are very popular, while several contents are significantly less popular. Using the zipf distribution for assigning the probability based on content popularity, the most popular contents are cached at the ES, so that the ES can serve several requests. Edge devices have smaller caching capacity available and therefore, fewer amounts of contents are stored at each ED and these contents have lower popularity index. This strategy helps the EDs to retrieve a large number of content from the ES without the need to use the link to the cloud. In this study, we assume that content popularity does not vary with time and we do not consider issues related to the the update of the catalog of contents with new contents to be distributed, nor we consider changes of content popularity. We assume for simplicity that data is refreshed at the ES and EDs only at low load periods when cloud resources and limited PLC capacity links can be utilized for content downloading and cache updating at both ends.

IV. SYSTEM MODEL

A. Content popularity and caching

Fig. 2 shows the content popularity that, as previously mentioned, is distributed according to the zipf distribution with parameter α. The contents are cached in the ES and the EDs according to the following rules:

- The most popular contents up to content M_1 are cached at the ES (1 hop from the devices). The probability that a request for content M is served by the ES is therefore: $P_\beta = P\{M \leq M_1\}$.
- Among the contents with popularity smaller than M_1, a number equal to $M_2 - M_1$ contents are stored in the EDs. Let the probability that a content is available at the EDs be denoted by $P_\gamma = P\{M_1 < M \leq M_2\}$. When a content is retrieved from another ED, it is uploaded to the ES and then transferred to the requesting ED. Moreover, P_{θ_i} is the probability that ED i requests a content that is stored in ED $i-$th own cache; we assume that contents between M_1 and M_2 are distributed in such a way that $P_{\theta_i} = P_\gamma / N$, where N represents number of EDs in the system.
- Finally, we indicate with P_L the probability that a content cannot be locally found and it should be retrieved from the cloud, if possible. It is $P_L = P\{M > M_2\} = 1 - P_\beta - P_\gamma$.

The probabilities P_β, P_γ, P_L can be easily derived from cumulative density function of zipf distribution.

$$F(x) = P(M \leq x) = \frac{H_{x,\alpha}}{H_{M,\alpha}} \tag{1}$$

where $H_{M,\alpha}$ is the $M-$th generalized harmonic number considering M number of contents cached in ES and ED.

B. Download from the ES

We assume that the requests from the $i-$th ED are generated according to a Poisson process with parameter λ_i and we denote by C_i the PLC link capacity between the ES and the $i-$th ED. All data requests that are served from the ES to ED i are served according to a processor sharing (PS) discipline over the link capacity C_i; i.e., assuming that when n services are in progress each one receives a capacity C_i/n. The PLC link from the ES to ED i is modeled as a $M/M/1$ queue with PS service discipline. The utilization of link i is:

$$\rho_i = \frac{\lambda_i (1 - P_L - P_{\theta_i}) \cdot x}{C_i} \tag{2}$$

where x is the average file size in bytes which we assume to be exponentially distributed. The term $(1 - P_L - P_{\theta_i})$ represents the probability of a requests is retrieved, directly or indirectly, through the ES.

When the content is available at the ES, assuming ideal fair scheduling of n active flows with processor sharing discipline, the average download time for a file of length x bytes experienced by ED i can be computed from the following expression:

$$d_i(x) = \frac{x/C_i}{1 - \rho_i} \tag{3}$$

C. Download from another ED

When the data is not found at the ES and content is retrieved from another ED, the average download time is then the time required to upload the content from the ED which stores the content to the ES that requests it plus the time to transfer the content to the ED which has performed the request. Since the requests fulfilled from other devices are much fewer in comparison to the requests directly served from the ES, the load in the uplink from the ED to the ES is small. Therefore, we suppose that the upload time, namely d_u, is simply the transmission time of an average file size of length x bytes over a link with capacity C_i, i.e., $d_u = x/C_i$. Moreover, the uplink and downlink capacity for the considered scenario is supposed to be the same.

Hence, the average download time T_i required by ED i for downloading the distributed content can be computed as:

$$T_i = \frac{P_\beta \cdot d_i(x) + (P_\gamma - P_{\theta_i}) \cdot (d_i(x) + d_u)}{P_\beta + P_\gamma - P_{\theta_i}} \tag{4}$$

where $d_i(x)$ is the average download time from the ES, as in (3).

For a no loss scenario, in which the EDs can retrieve the content from the cloud link if it is locally unavailable, the

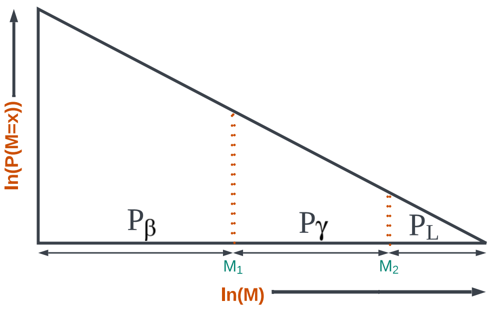


Fig. 2: Distribution of content with Zipf

average download time is given by:

$$T_{avg} = \frac{P_\beta \cdot d_i(x) + (d_i(x) + d_u) \cdot (P_\gamma - P_{\theta_i}) + d_{cl} \cdot P_L}{1 - P_{\theta_i}} \qquad (5)$$

where d_{cl} is the average download time from the cloud link which can be computed as a ratio of the average file size and the available capacity of the cloud link.

V. SCENARIOS

For analyzing the proposed cooperative caching in low capacity PLC network we consider the following three scenarios:

- **Collaborative Caching with Full-Cloud link:** A requested contents can be fetched from the cloud if it is not locally available from the ES and the EDs. Assuming that the bottleneck is on the link between the the ES and the EDs, the delay can be computed from (3).
- **Collaborative caching with Losses:** Losses account for the content which is neither stored in ES nor in EDs and furthermore, t The link between the cloud and ES is not available for downloading and then a request for a content is lost. The requests is dropped by the ES.
- **Collaborative Caching with partial Cloud link:** In this case, only a portion of the capacity of the backhaul link towards the cloud is available for video on demand (VOD). Considering the presented remote area situation, it would be expensive to use the link between the ES and the cloud for VOD when demand for services is high, like at peak hour, due to the link limited capacity. In this case, the backhaul link behaves like a bottleneck and the download time is large but there are no losses in the system.

VI. PERFORMANCE EVALUATION

A. Simulation setup

Our model comprises of a small network with $N = 5$ EDs and an ES. The bandwidth of the PLC link between the ES and each ED has a capacity of 20 Mbps. Furthermore, the Zipf distribution is used to define the popularity of content, as well as the placement of content within the network. On average we considered 1000 video files cached between ES and EDs, where We divide the cache space in a such a way that the 70% of most popular contents are placed in the ES and the remaining 30% are divided equally at the EDs. Whereas the contents belonging to the tail of the popularity distribution is neither stored in ES nor in the EDs and can only be fetched from the cloud upon availability of resources. A total of $M = 10,000$ video files are considered. The inter-arrival time of the requests is exponentially distributed with parameter λ_i for each ED i.

To validate our model, a simulator is designed in python using SimPy library. We have assumed a constant file size of 420 MB for the simulation purpose, and the length of each packet is considered to be 1500 B. The simulation parameters are presented in Table I for brevity. According to the zipf distribution, each file has been associated a probability of demand based on the popularity of that file, hence a random file is requested among M files.

TABLE I: Simulation Parameters.

Parameters	**Symbols**	**Values**
Video file size	x	420MB
PLC link capacity (ES to ED)	C_i	20Mbps
Cloud link capacity for VOD	C_p	10Mpbs
Packet length	x_m	1500B
Total number of video files	M	10000
zipf parameter	α	$[0.2, 0.4, 0.6, 0.8, 1]$
Video request rate	λ	$[1] \cdot 10^{-3}$ s^{-1}
Number of EDs	N	5

B. Performance Evaluation metrics

To objectify the performance of different collaborative caching scenarios, the following metrics are considered.

Cache Hit Ratio: A request for a content is termed cache Hit if the requested content is found locally stored in the caches (served by either the ES or the EDs). When a request is transferred to the cloud or, if the cloud link is not available, is lost, there is a cache miss. Then, the cache hit ratio is defined as:

$$CHR = H/T = 1 - N/T \qquad (6)$$

where T is the total number of requests, H and N are number of cache hits and cache misses respectively.

Average downloading cost: This refers to the ratio of the average downloading time for collaborative caching through local caches (ES and EDs), with respect to the total average downloading time T_{avg}, which can be derived from (5).

$$D_{local} = \frac{P_\beta \cdot d_i(x) + (P_\gamma - P_{\theta_i}) \cdot (d_i(x) + d_u)}{T_{avg}} \qquad (7)$$

Similarly, the cost to retrieve the content from the cloud is:

$$D_{cloud} = \frac{d_{cl} \cdot P_L}{T_{avg}} \qquad (8)$$

where d_{cl} is the average download time from partial cloud link.

C. Impact of zipf parameter α

In Fig. 3, we observe the impact of the skewness parameter α of the zipf distribution on the probability that the file is downloaded from the ES, EDs and loss probability when cloud resources cannot be utilized. As α grows, the zipf distribution

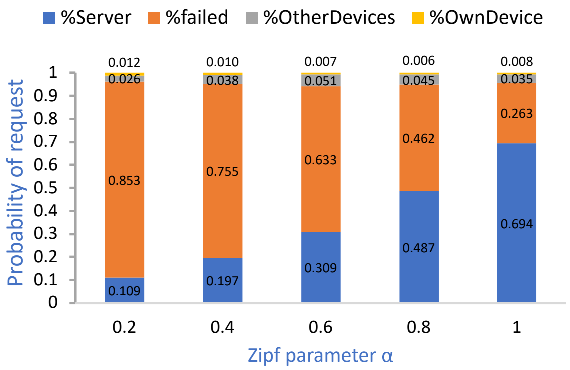


Fig. 3: Probability of file request served locally, by the ES, the EDs and lost, under varying zipf distribution parameter α and request rate equal to $0.0001 s^{-1}$.

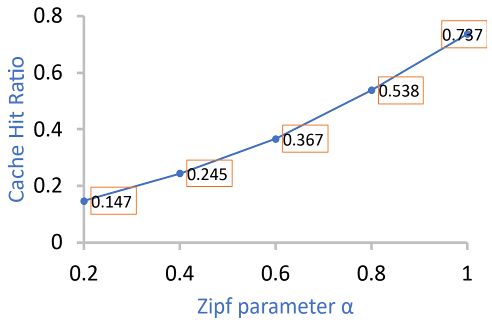
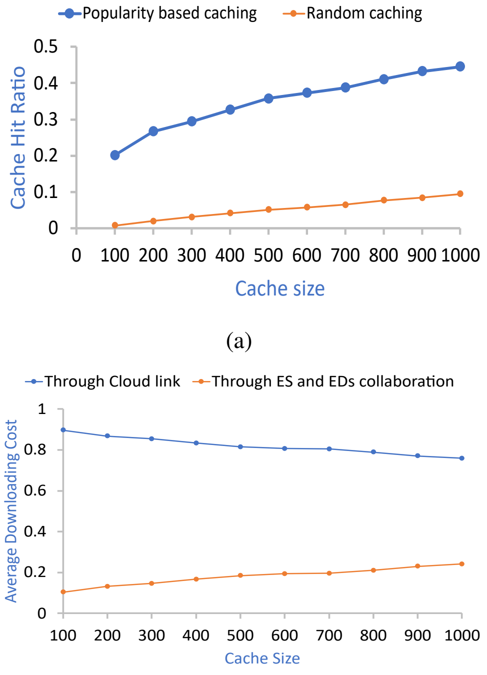


Fig. 4: Cache Hit ratio for varying zipf distribution parameter α and request rate equal to $0.0001 s^{-1}$.

is further skewed and, consequently, the probability associated with the most popular contents increases. As a result, most of the content requests are directed towards the ES, where 50% of the most popular contents are stored. Moreover, with large values of α, fewer requests correspond to the contents stored in EDs. Similarly, the probability of not serving a request reduces as α grows. In the scenario where the file request can be forwarded to the cloud when we can spare the resources for VOD traffic, the probabilities that are termed in the legend as ”failed” will be considered as probability of contents that are requested from the cloud. Fig. 4 describes the cache hit ratio for varying zipf parameter α. As α increases, the probability of requesting most popular content increases, and this leads to a better cache hit ratio, since the content would probably found from the ES or the EDs.

D. Performance Comparison with varying cache size

Fig. 5a shows the performance in terms of cache hit ratio for the proposed collaborative caching technique for popularity based data caching in comparison with random caching with varying cache size. We suppose that the number of contents equal to 10,000, while the popularity parameter α is 0.7. We increase the cache size of ES and EDs in proportion of 70 ratio 30 (e.g cache size 100 reflects that ES cache storage capacity is 70 while remaining capacity is divided among the number of EDs). Results show that increasing the cache size improves the cache hit ratio for both techniques, however with popularity based caching, the collaborative caching performs up to 3 times better compared to random caching.



(a)

(b)

Fig. 5: Performance comparison with varying cache size (a) Cache Hit Ratio for Popularity based caching and random caching (b) Average Downloading Cost for serving a request through collaborative caching and partially available cloud link

Fig. 5b compares the average downloading cost of contents downloaded through the cloud with with partially available capacity i.e 10Mbps, and through local caching system between ES and EDs. The results reveal the usefulness of the proposed technique for the low capacity PLC network. As PLC link budget is constrained, the average file downloading cost through collaborative caching between local nodes, ES and EDs, is much smaller than the cost of downloading through the cloud link. Hence, caching of most popular contents at user premises support better utilization of PLC network resources in terms of bandwidth as well as delay. The results also show that by increasing the cache size, the cache size impact on the average downloading cost increases, since more contents can be retrieved locally, whereas the load on the cloud link decreases, and the average downloading cost of cloud link decreases as well.

E. Average Download time

Fig. 6 shows the average download time obtained under the assumption of cloud link with partial available capacity i.e., 10 $Mbps$. The resources of cloud link are only partially utilized for data downloading purpose and rather saved for more crucial services. Though with partial availability of cloud link, the

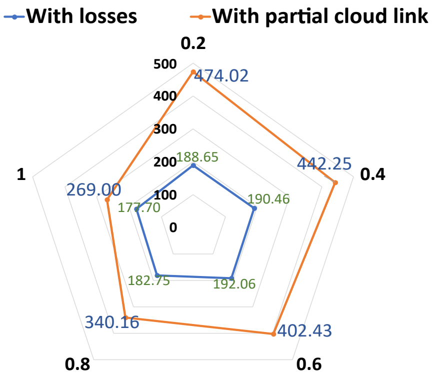


Fig. 6: Comparison analysis of average download time associated with partial-cloud link and system with losses under varying zipf distribution parameter α.

losses are reduced but the delay increases. Fig. 6 reveals the effect of zipf distribution parameter α for both scenarios. As the skewness parameter α increases, collaborative caching performs better due to increase in probability of request of most popular content that is locally available from ES and EDs and this will eventually relieve the burden on precious cloud link. However, We can utilize partial cloud link in case of low network congestion periods, whereas for high load periods, we can retrieve upto 78% of the content locally from ES and EDs with much less downloading delays.

Nevertheless, we can clearly analyze from the results that though the cloud solution mitigates losses from the system it corresponds to larger download delays. Conversely, the popularity driven proposed collaborative sharing system reduces the delays associated with content downloading, while limiting the use of the backhaul link.

VII. CONCLUSION

One of the key challenges today is closing the digital divide through providing connectivity by means of affordable solutions with sufficient data rates and availability in remote and rural areas. PLC is considered to be an efficient method to bring connectivity using the existing power infrastructure. However, PLC has limited capacity which could effect the provisioning of video services that are based on the download of large data files. Edge caching helps in pushing the contents at network edge or user premises and it leads to improve the delays in retrieving the content and, in this case, in reducing the burden on PLC backhaul links. This paper investigates the performance of PLC network merged with edge caching through a collaborative caching scheme in which a cache facility is deployed at a server node as well as at user nodes. Our results show that the application of the collaborative caching scheme can reduce the average download time with respect to fetching the content from the cloud resources and reduces the load on low capacity PLC links.

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