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A Fog Caching Scheme Enabled by ICN for IoT Environments

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Abstract

The rapid growth in computation and processing power of end-user devices has transitioned network functionalities from the core network to the Fog, thus, reducing response times and ultimately improving user experience. The Information-Centric Networking paradigm aims to transform conventional content caching and delivery approaches by enabling Fog nodes to participate in both forwarding and caching. In this work, a Fog caching design scheme is presented for applications such as Internet-of-Things, which integrates three novel design attributes. Firstly, a Fog cluster-based scheme is proposed that utilises both in-network and end-user devices to cache content closer to the edge network, according to the increasing popularity of the content. Secondly, this work proposes a near-path approach that leverages caching nodes near the content delivery path. Finally, by craftily integrating reactive and proactive caching, congestion during network peak-time is averted. Simulations are conducted in the Icarus environment and evaluated against eight popular benchmark techniques. The results indicate significant improvement in internal link load and path stretch metrics. Finally, the cache hit ratio metric is consistently better than all other benchmarks, while the latency performance of the proposed scheme is competitive when the content distribution is more concentrated.

Keywords: In-network Caching; Information-Centric Network; Peer-to-Peer Cache; User Generated Content; Content Delivery; Content Placement Strategy.

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1. Introduction

Internet-of-Things (IoT) is gradually establishing itself as a driving force for technological advancement creating impact in multiple sectors, including smart homes and cities, intelligent transport systems, industrial control systems and even e-health services. Despite the new technological opportunities, a number of IoT related challenges arise. In particular, the security of sensitive IoT data is paramount due to privacy concerns [1]. In addition, the sheer volume of IoT traffic and the immediate response time expected from IoT services mandate novel approaches towards load balancing and delay tolerance [2].

Information-Centric Networking (ICN), a next generation network architecture, adopts a content-centric approach that could be used for IoT content delivery, whilst abiding to security related requirements [3]. The inherent in-network caching capability of ICN also has the potential to significantly reduce the traffic load and transmission delay in next-generation networks [4, 5].

With the rapid growth of computational and storage capabilities in IoT devices, network functions, such as content delivery and load balancing, could transition from the network core to the Fog. To this end, there is an increasing research momentum for utilising the ICN architecture to address challenges in Fog networks. The authors in [6] present an overview of the challenges and development road-map for Data-Centric IoT in the Fog. The authors in [7] overcome session disruptions due to the ad-hoc nature of Fog networks, by using qualifiers that Fog nodes must present in order to receive data in an ICN paradigm. Furthermore, to extend the conventional Fog-to-Cloud communication paradigm, the authors in [8] introduce a horizontal Fog-to-Fog communication layer enabled through ICN.

In a similar spirit, this work aims to design a Fog-caching scheme for IoT applications leveraging the ICN architecture. Specifically, according to our comprehensive investigation, as described in the next section, six caching design drivers are identified in existing in-network caching approaches. Conventional works in this area are focusing on a subset of these drivers. To incorporate all six drivers, our proposed scheme design meets three unique attributes, as follows.

Firstly, the caching nodes within the network Fog compose one or more adjustable sets, Fog-Clusters (*FCs*), each serving a group of users for a fixed period of time. During the caching process, the requested contents are initially cached into the Fog's highest tier caches. As the content gets increasingly requested, it is gradually cached in
35 lower tiers, i.e. closer to the user side. In order to adjust to topology changes and utilise potential available storage resources, both in-network and end-user caching devices, the cluster border can periodically be extended towards upper and/or lower tiers.

Secondly, instead of traditional on-path and off-path caching [9], caching nodes *near* the delivery path are also considered as elements in the *FC*. In this way, the commonly
40 demanded content can be cached close to multiple delivery paths and increase the caching node utilisation.

Finally, as an integration of reactive and proactive caching, full-time caching is introduced to reduce delivery delay and peak-time traffic load. In full-time caching, reactive caching is triggered only once, when the content is delivered from its original
45 provider to the end-user. Thus, at least one content could be cached in Fog caching nodes. Proactive caching is only triggered in off-peak hours to populate Fog caching nodes without incurring excessive traffic during peak-time content delivery.

The original contribution of the paper is summarised as follows:

- A novel caching scheme is proposed that incorporates six identified drivers
50 through comprehensive investigation of conventional in-network caching schemes. Specifically, the proposed scheme has three outstanding attributes: 1) flexibility achieved through periodically adjustable clusters 2) near-path content allocation utilising node near the delivery path and 3) full-time caching, combining proactive and reactive approaches.
- The proposed caching system is modelled in two parts. Initially, set theory
55 is applied to assign permanent characters, which represent the forwarding and storage capabilities of each node. In addition, temporary roles dictated by logical coordinates are allocated to identify the cluster and tier of involved caching nodes during a particular content request session.
- Simulated experiments are designed to model a dense Fog caching environment
60

for IoT applications. In our experimental design, both end-devices and ICN in-network nodes are configured for caching purposes. Moreover, the dependence on the backbone network is limited and emphasis is placed on the network Fog. To design scenarios of mixed request traffic, a number of end devices are nominated as data sources for both user-generated content and content-on-demand.

- The proposed scheme achieves better performance in four evaluation metrics; latency, cache hit ratio, internal link load and path stretch. Evaluation and analysis is conducted against popular schemes i.e. Edge Caching, Consumer Caching, Leave Copy Down [10], Leave Copy Everywhere, Random Choice [11], Random Bernoulli, [12], Cache Less for More [13] and ProbCache [14].

The rest of this paper is structured as follows. Section 2 summarises the state-of-the-art ICN Fog caching schemes for IoT applications according to six design drivers. The proposed system design is presented in Section 3, where three attributes that satisfy the design drivers are illustrated. Section 4 describes the proposed system model and describe how permanent characters and temporary roles are allocated to Fog nodes. Section 5 provides the algorithmic implementation of the proposed scheme. The experimental setting, including parameter configuration, topology design and performance metrics are described in Section 6, followed by the result discussion in Section 7. Finally, the paper concludes in Section 8 with a discussion on future work.

2. Related Work

With the rapid development of IoT technologies, the research emphasis of ICN architectures is moving towards the network Fog and Edge [15]. For example, some researchers combine the Named Data Network (NDN) architecture with Edge computing to meet the IoT requirements [16]. In addition, others suggest to apply deep-learning intelligence on the ICN-IoT platform at the network Edge to provide better services [17]. However, since the ICN concept was firstly proposed in the TRIAD project [18], the multiple naming and resolution design push the ICN approaches into several distinct directions [19]. For instance, some ICN architecture, such as NDN [20] adopts

hierarchical naming or naming schemes with attribute-based features [21], while others,
90 such as DONA [22] and PURSUIT [23], select flat naming method in their design
[24]. Nevertheless, in-network caching is an essential and common component in ICN
architectures, especially at the network Fog.

In the following paragraphs, the conventional in-network caching literature can be
categorised according to six design drivers.

95 **1. Caching Granularity:** Regarding the granularity of cached content, the existing
schemes have attempted to store the content in packets, chunks or object units. The
typical packet-level caching scheme was initially proposed by the authors in [25] and
explores the feasibility of functional network-level packet caches in ICN routers. For
chunk-level caching, WAVE [26] splits content into chunks, and contents popularity is
100 used to determine the number of cached chunks for specific content. In addition, coded
caching [27] also splits the content into chunks and caches the chunks for the same
content in different caching nodes. According to the authors in [28], coded caching
can achieve better performance than uncoded schemes in broadband multi-media ser-
vices, such as video-on-demand (VoD). However, in most IoT applications, the contents
105 are not only on-demand but also generated by end-users. Thus, considering such IoT
traffic patterns, object level caching is better suited to the design characteristics of the
proposed IoT-oriented scheme, due to the lower delay tolerance, smaller content size,
larger number of contents and shorter expiration time in User Generated Content [29].

2. Caching Node Placement: Conventional literature in caching node placement
110 could be divided into ubiquitous caching, Fog caching and Edge caching. Compared to
ubiquitous caching with high management cost [30] and Edge caching with restricted
end-device capacity [31], the Fog placement is emerging as an ideal caching position
for some applications [32]. Moreover, adjustable Fog caching, which can work together
with end-user caching devices and conventional storage servers, is motivated by the
115 intrinsically hierarchical “Cloud-Fog-Edge” network architecture [33]. Thus, our pro-
posed scheme focuses on adjustable and distributed Fog-caches incorporating end-user
and in-network caching nodes.

3. Storage Capacity Allocation To explore the efficient storage allocation, the authors
in [34] compared heterogeneous allocation with homogeneous cache size distribution.

120 Their result indicated that the improvement of heterogeneous allocation based on topological graph properties is very limited. Thus, the storage capacity allocation in the proposed scheme chooses a homogeneous distribution, meaning that the caching capacity of every caching node is uniform.

4. Caching Timing: Caching timing determines when the caching operation is triggered. In conventional schemes, the caching timing may be either reactive or proactive [35]. Reactive caching means the caching operation is only triggered during the content delivery session [36]. On the other hand, proactive caching schemes populate the caching nodes regularly but outside the delivery session (e.g. during off-peak hours) [37]. In this paper, a full-time scheme is introduced as a combination for reactive and proactive caching.

5. Content Eviction: Once caching nodes get full, there is a need for content eviction schemes to release the caching space for the new coming contents. So far, most of the conventional content eviction algorithms are derived from the cache replacement ones for operational system caching. Aiming at the ideal Belady's MIN [38], basic policies (i.e. First-In-First-Out (FIFO), Least Frequently Used (LFU), Least Recently Used (LRU)) based on content freshness, content request frequency and request recentness are used for content eviction purposes. Since almost all the conventional caching schemes use LRU, a line speed scheme, in their implementation, the proposed scheme also uses LRU to maintain an fairness in evaluation.

140 **6. Content Placement:** Content placement is the most active research topic and is responsible for deciding which nodes will cache a particular content. Based on whether contents are placed into caching nodes on or out of the delivery path, conventional caching schemes are categorised into on-path or off-path. Most of the existing schemes in the literature are on-path schemes. For example, Leave Copy Everywhere (LCE), random probabilistic caching (RND), UniCache, Random Insertion (RAND) and Leave Copy Down (LCD) [10] are typical on-path content placement strategies [39].

LCE caches the content in every single caching node along the delivery path. In order to reduce LCE's excessive caching, RND and UniCache introduce a caching probability. In RND, the content is cached into each on-path caching node following a randomly generated probability. UniCache uses a fixed probability equal to the inverse

of the hop-distance of the delivery path and, as a result, caches a specific requested content only in a single location along the delivery path. Similarly, LCD and RAND are two other caching strategies, which cache a content once along each delivery path. Under the LCD strategy, the content's caching position is moved towards the end-users with increasing number of requests. In RAND, a random node on the delivery path is selected to cache the content. Besides the traditional strategies mentioned above, some more comprehensive content placement strategies have been proposed according to different criteria, such as content popularity and probability.

WAVE [26] is a popularity-based strategy, in which the content is split into chunks during the caching process. The number of cached content chunks in each caching node is exponentially increased along with the increasing number of request. In addition, ProbCache is another probability-based strategy [14], in which the probability of caching is calculated and stored in every caching node depending on several factors, such as hop distance from source and caching space remaining on the path. Furthermore, Popularity based Probability Caching [40] is based on both content probability and popularity and can enhance the content delivery services in named data networks.

Furthermore, the graph properties of a network topology could also be used to decide on content placement. For example, Cache Less for More (CL4M) selects the betweenness centrality graph property. When the content is delivered towards the user, a content is left into the caching node with the highest betweenness centrality value. The criteria for content placement decision could also be a combination of topological information and content characteristics [13]. For example, Age-based Cooperative Caching (ABC) assigns a lifetime to each content when it is cached [41]. The lifetime is computed depending on node location and content popularity and once the lifetime expires, the content is removed. In contrast to on-path strategies mentioned in the literature, the proposed scheme gathers the caching nodes close to the delivery path as steers, and is referred to as a "near-path" cluster-based scheme.

In summary, most conventional works are characterised by a subset of these six design drivers. The proposed scheme is the first Fog-caching enabled design for IoT scenarios that considers all six drivers of in-network caching. The detailed design of the proposed scheme is explained in next section.

3. System Design

Compared against conventional caching schemes, the proposed Fog-caching scheme offers adjustable, cluster-based, near path and full time caching attributes. The details of these attributes are explained in the following sub-sections.

3.1. Flexibility: Adjustable Clusters

The proposed scheme places emphasis on utilising the Fog-nodes for caching purposes. Once the first content request emerges from a group of users, the distributed caching nodes are grouped into *FCs*. Specifically, based on the topology of all caching nodes within a *FC*, multiple tiers are formed, as seen in Fig. 1. In each cluster, the

Figure 1: A schematic representation of the proposed *FC* design scheme with respect to the backbone and Edge, corresponding tiers and individual components Top and Bottom Cache nodes, which are used in the full-time caching attribute.

caching nodes close to the end-user devices and the core network are defined as lower and upper tier caches, respectively.

In contrast to ubiquitous caching, the proposed scheme disregards caching capacity of nodes located beyond a preset distance away from the end-user devices. To this end, the highest tier value is assigned in advance, and is determined according to the graph radius of a given network topology.

After a content request is raised, the lowest-tier Fog-nodes are firstly queried, before continuing to higher tiers. If the requested content exists in the t^{th} tier nodes, it is delivered to the user and the content is subsequently shifted one tier closer ($t - 1$) to the end-users, ensuring close proximity to users for future content requests. If the requested content is not found in the highest tier, the request message is directly routed to the original content provider at the core network, without any further attempts at the backbone network as happening in ubiquitous caching schemes. In this case, the content is cached into a randomly selected caching node in the highest possible caching tier, which is referred as “Top Cache”.

Despite the available storage capacity in end-user devices, sharing it for caching purposes with the rest of the Fog-nodes is optional, rather than enforced. An advantage of the proposed adjustable scheme is the ad-hoc creation of a tier 0, only when such end-devices are willing to allow their storage to be used as a caching resource. Let us assume that a content request emerges from an IoT end-device, e.g. *User 1* in Fig. 1. The corresponding *FC* spans tier 1 (*Cache 1*, *Cache 2*), tier 2 (*Cache 3*) and tier 3 (*Cache 4*). If there is at least one end-user device allowing access to its storage capacity, then tier 0 for this *FC* is automatically enabled, consisting of all peer caching devices that allow storage access. Note, that peer caching device refers to the shared caching resources of end-user devices as described in [42]. On the other hand, if there is no available end-user device detected, the lowest caching tier would default to tier 1, consisting of the caching nodes closest to the end-users (*Cache 1*, *Cache 2*). Similarly, if there is a content delivery proxy server available at the edge of the network core (*Proxy Server in tier 4*), the *FC* can expand towards the core network side to include a higher tier caching location.

3.2. Near-Path: Caching near the delivery path

Regarding content placement, most of existing in-network caching schemes adopt an on-path caching scheme because searching for content beyond the delivery path requires additional traffic, thus increasing network load, without guaranteeing success. However, in the IoT Fog environment, the delivery path is unpredictable due to its ad-hoc and continuously evolving nature. Thus, if only caching nodes on the delivery

path have opportunities to be hit, the nearby (i.e. near-path) resources are not utilised.

In order to trade-off the cost between searching for content and excessive storage, the proposed scheme adopts a hybrid, near-path solution. When the first content request emerges from a new user group, the respective *FC* is constructed to offer caching services near the delivery path. In this way, the redundancy of contents may be reduced by sharing popular contents among multiple end-user devices. In addition to *FC*, end-user devices, which are less than two hops away from each other (the optional intermediate hop would be either cellular base stations or wifi access points) compose user-clusters (*UCs*). The group of users from one or more *UCs* can share the caching resources in the same near-path *FC*.

3.3. Full-Time: Combination of Reactive and Proactive Caching

To reduce the link load during peak time, the full-time caching timing design diverts the arising content allocation traffic to off-peak content delivery hours. Specifically, in the full-time caching proposal, only a single cache of requested content is placed in the allocated *FC* during the content delivery process, which is the reactive caching slot. Once the user request is successfully satisfied, the cached content would be duplicated and distributed into other caching nodes in the *FC*, during off-peak hours, which is the proactive caching slot. In this way, delivery delay could be reduced by decreasing content populating traffic during the peak of content demand.

4. System Model

In this section, the system model of the proposed Fog-caching scheme is described through the permanent character assignment and temporary role allocation. In order to construct a node's potential during a delivery session, node capabilities, such as caching ability, are identified and recorded as permanent characters, once a new content request is generated from a user device.

The role of each caching node is a logical caching coordinate representing the *FC*, tier number, and identity (ID) of the node. During the process for cache allocation, this information is used to determine in which node the requested content should be cached.

255 Once all nodes are allocated a character and role, a bespoke FC is mapped to the whole user group that it may serve.

4.1. Permanent Character Assignment

In the proposed system, the Fog-network topology graph is denoted by $G = (V, E)$, where V is the set of vertexes in a topology graph (set of nodes) and E represents the graph edges (i.e. links between nodes). Specifically, each node, $v_i \in V$, has a unique id, i . Each node v_i may belong to one or more of the following character sets:

1. *Set of user devices, U* : Includes end-user devices that initiate content delivery sessions by sending request messages for contents.
2. *Set of forwarding hops, H* : Includes nodes with message forwarding capability.
- 265 3. *Set of content providers, P* : Includes nodes that are original content providers. In the case of user generated content, the node is also a user device, thus $v_i \in (U \cap P)$.
4. *Set of caching hops, C* . Includes nodes with caching capacity. Such node may either be a standalone caching node, an ICN router, $v_i \in (C \cap H)$, or a peer user allowing access to its storage, $v_i \in (C \cap U)$.

Character	Node Set
End-user device	$U = \{v_i\}, i \in [10, 15]$
Caching hop	$C = U \cup \{v_i\}, i \in [1, 6]$
Forwarding hop	$H = \{v_i\}, i \in [1, 8]$
Content provider	$P = \{v_9, v_{10}, v_{13}\}$
Caching & Forwarding hop	$C \cap H = \{v_i\}, i \in [1, 6]$
End-user & Content provider	$U \cap P = \{v_{10}, v_{13}\}$

Table 1: Character assignment for all nodes in the example topology of Fig. 2. All end-user devices are able to cache content, and end-users v_{10}, v_{13} are also original content providers.

270 Fig. 2 shows an example topology to illustrate the character allocation. Access points v_1 and v_2 are connected with ICN routers $v_3 - v_5$ and $v_4 - v_6$, respectively, at the network Fog.

Figure 2: An example of a Fog network topology to illustrate the character and role allocation, based on the capabilities and tier of every node. The diagram illustrates the borders of UC_1 , UC_2 , FC_1 and FC_2 . Note, that nodes v_4 and v_5 belong to both FC_1 and FC_2 .

Since nodes $v_1 - v_6$ have both caching and forwarding capability, they belong to both C and H sets. Nodes $v_7 - v_9$ are at the edge of the core network and are only forwarding devices without caching capacity. Node v_9 at the core network is the source of original content. In addition, since this paper is focusing on user generated video, two end-user devices are assumed to be potential content providers ($v_{10}, v_{13} \in P$). The character assignment for all nodes in Fig. 2 is summarised in Table 1.

4.2. Temporary Role Allocation

As mentioned in the design section, there are two types of clusters in the proposed caching scheme, which are UC and FC . The nodes within the same FC work collaboratively to concurrently serve one or more UC s and each end-user device may belong to at least one UC .

Fig. 2 shows users $v_{10}-v_{12}$ clustered in UC_1 , while users $v_{13}-v_{15}$ are clustered in UC_2 . If a user devices does not have caching capacity then it can only be included in a UC , but not in a FC . Note, that it is possible for a Fog node to belong to more than one FC s, such as v_4 and v_5 that belong to both FC_1 and FC_2 .

Node	If no end-users can cache			If end-users can cache		
	Cluster	tier	Role	Cluster	tier	Role
v_2	FC_2	1	(2, 1, 2)	FC_1	1	(2, 1, 2)
v_4	FC_1	2	(1, 2, 4)	FC_1	2	(1, 2, 4)
	FC_2	2	(2, 2, 4)	FC_2	2	(2, 2, 4)
v_5	FC_1	2	(1, 2, 5)	FC_1	2	(1, 2, 5)
	FC_2	2	(2, 2, 5)	FC_2	2	(2, 2, 5)
v_{11}	N/A	N/A	N/A	FC_1	0	(1, 0, 11)
v_{14}	N/A	N/A	N/A	FC_2	0	(2, 0, 14)

Table 2: Logical caching coordinates (roles) of five nodes from the example Fog topology of Fig. 2 in two scenarios: When no end-user has caching capability and when end-users do have caching capacity.

A node's role encodes its position in the Fog network topology. For example, in Fig. 2, caching node v_3 has role (1, 2, 3), represent FC_1 , tier 2 and node $id = 3$. Table 2 presents several other node roles from Fig. 2 in the case when all end-users are able to cache and when they can not.

5. System Implementation

The system implementation of the proposed scheme consists of three steps: 1) Preparation, 2) Request message routing and delivery and 3) Content delivery to end-user and caching content closer to end-users for future use. There are 8 algorithms presented in this section. Algorithms 1-3 are used during the first step, algorithms 4-6 during the second step and the final 2 algorithms during the third step.

5.1. Step 1 Preparation

The preparation step, Alg. 1, is responsible for constructing the FC for a specific user group based on the individual node character assignment and role allocation, as described in Section 4. A Boolean logic peer flag, F_p , is used to indicate whether tier 0 exists. Only when there are peer end-user devices with caching character in the same tier as the content requester, is F_p set to 1. In addition, during the preparation

Algorithm 1 Preparation

Input: Requesting end-user device v_u , requested content k

Output: Original content provider v_{pk} , peer flag F_p , FC ζ , node caching sets in every tier $\zeta^{(0)}, \zeta^{(1)}, \dots, \zeta^{(max)}$, Bottom cache node v_{Bottom} , Top cache node v_{Top}

```
1: Obtain the original content provider,  $v_{pk}$ , for content,  $k$ 
2: Identify the highest,  $max$ , tier bound
3: Prepare  $\zeta^{(0)}$  using peer cache composition (see Alg. 2):  $\zeta^{(0)} \leftarrow \text{peer\_cache}(v_u)$ 
4: if  $\zeta^{(0)} \neq \emptyset$  then
5:     Assign Boolean value 1 to the peer flag  $F_p$ :  $F_p \leftarrow 1$ 
6: else
7:     Assign Boolean value 0 to the peer flag  $F_p$ :  $F_p \leftarrow 0$ 
8: Obtain the routing path between  $v_u$  and  $v_{pk}$ 
9:  $tier1 \leftarrow \text{False}$ 
10: while  $tier1 = \text{False}$  do
11:     for all pair of neighbour nodes  $(v_i, v_j)$  on the delivery path do
12:         check the caching character of the latter node  $v_j$ 
13:         if  $v_j$  has caching character then
14:             Add  $v_j$  to  $\zeta^{(1)}$ ,  $tier1 \leftarrow \text{True}$ 
15: if  $(\zeta^{(1)} \neq \emptyset)$  and  $(max. \geq 2)$  then
16:     for  $t$  existing between 2 and  $max$  do
17:         Prepare  $\zeta^{(t)}$  by searching caches in tier  $t$  (see Alg. 3):
             $\zeta^{(t)} \leftarrow \text{tier\_t}(\zeta^{(1)}, t, v_{pk})$ 
18: if  $\zeta \neq \emptyset$  then
19:      $v_{Bottom} \leftarrow$  choose a node randomly from  $\zeta^{(min.)}$ 
20:     if  $\zeta$  has only one tier,  $min. = max.$ , then
21:          $v_{Top}$  is the node as  $v_{Bottom}$ :  $v_{Top} \leftarrow v_{Bottom}$ 
22:     else
23:          $v_{Top} \leftarrow$  choose a node randomly from  $\zeta^{(max.)}$ 
24: return  $v_{pk}, F_p, \zeta^{(0)}, \zeta^{(1)}, \dots, \zeta^{(max)}, v_{Bottom}, v_{Top}$ 
```

step a Bottom and Top caching nodes are nominated to be used during the request
 305 message routing (step 2) and caching (step 3), respectively, as will be detailed in later
 subsections.

More specifically, the original content k provider node, v_{pk} , where pk is the node's
 id, is found and recorded (line 1) along with identifying the highest, max , tier number
 (line 2). Then, by calling function `peer_cache()` (Alg. 2), the caching character of
 310 every peer user-device is detected. If there are peer devices with caching character,
 they are included in tier 0 set, $\zeta^{(0)}$, and the peer flag, F_p is set to 1. Otherwise, tier 0
 is empty and F_p is set to 0 (lines 3-7).

Once the routing path from the requesting end-user, v_u , to the original content
 provider v_{pk} is identified (line 8), the node for tier 1 is found along the delivery path
 315 and put in set $\zeta^{(1)}$ (lines 9-14) and, then nodes belonging in tier t are included in set $\zeta^{(t)}$
 (lines 15-17). Finally, for future routing and caching purposes, the Bottom, v_{Bottom} ,
 and Top, v_{Top} , cache nodes are randomly selected from the lowest and highest tiers
 of ζ , respectively (lines 18-23). Note, that in the case when there is only one tier, the
 Bottom and Top cache nodes are the same node (line 21).

320 The peer cache composition function `peer_cache()`, shown in Alg. 2, aims to
 collect all peer nodes with caching character in set $\zeta^{(0)}$. Initially, the set of peer caching
 nodes $\zeta^{(0)}$ is an empty set (line 1). Then, for all end-user devices in UC , besides v_u
 itself, their caching character and hop distance from the requesting end-user, v_u , are
 checked. If an end-user's distance is equal to or less than two hops away from v_u (e.g.
 325 users v_{10} and v_{11} in Fig. 2 are two hops (v_1 away) and has caching character, then it is
 included in tier 0 set $\zeta^{(0)}$ (lines 3-4).

Similarly, the tier cache composition function `tier_t()`, shown in Alg. 3, aims to
 collect all tier nodes higher than tier 1, $t \geq 2$, in set $\zeta^{(t)}$. Initially, the set of tier caching
 nodes $\zeta^{(t)}$ is an empty set (line 1). Any node, v_j , with caching character and $(t - 1)$
 330 hop distance from tier 1 will be included in the set $\zeta^{(t)}$ (lines 3, 4). For example, in
 Fig. 2, node v_3 from v_1 is 1 hop away. In general, nodes in tier 2, $t = 2$, will be $t - 1 = 1$
 hops away from tier 1 nodes, nodes in tier 3 will be $t - 1 = 2$ hops away from tier 1
 nodes, an so forth.

Algorithm 2 Peer Cache Composition: peer_cache()

Input: Requesting end-user device v_u

Output: Tier 0 peer caching nodes $\zeta^{(0)}$

- 1: Initialise $\zeta^{(0)}$ as an empty set
 - 2: **for** each end-user devices v_i in current user group **do**
 - 3: **if** (v_i has caching character) and $v_i \neq v_u$ and (hop distance between v_i and v_u is less or equal to 2) **then**
 - 4: Add v_i into set $\zeta^{(0)}$
 - 5: **return** $\zeta^{(0)}$
-

Algorithm 3 Tier $t \geq 1$ Composition: tier_t()

Input: Tier 1 caching nodes $\zeta^{(1)}$, queried tier t , original content provider v_{pk}

Output: Set of tier t caching nodes, $\zeta^{(t)}$

- 1: Initialise $\zeta^{(t)}$ as an empty set
 - 2: **for** node v_i in the first tier, $v_i \in \zeta^{(1)}$, **do**
 - 3: **for** every node v_j with caching character, $v_j \in C$, **do**
 - 4: **if** (hop distance between v_i and v_j is $(t - 1)$) and (hop distance between v_j and v_{pk} is less than hop distance between v_i and v_{pk}) **then**
 - 5: Add caching node v_j into set $\zeta^{(t)}$
 - 6: **return** $\zeta^{(t)}$
-

5.2. Step 2 Request Routing and Delivery

335 During the request message routing and delivery, the Bottom cache node, selected in the preparation step, is delegated to forward the content request message in order to identify in which node and tier the requested content is located. To this end, tier 0 is initially searched (Alg. 4), since it is the closest to the end-user. If the content is not found in tier 0 and if there are higher tiers, searching continues in those higher tiers
340 (Alg. 6), i.e. in in-network nodes. If there are no available caching nodes in higher tiers, the content request message is forwarded directly to the original content provider (Alg. 5).

Algorithm 4 Request message routing & delivery within Tier 0

Input: Requesting end-user device v_u , requested content k , original content provider v_{pk} , FC
 ζ , peer flag F_p

Output: (If cache hit in tier 0) serving node ID id_s , serving flag F_s , boolean value $CacheHit$

```
1:  $CacheHit \leftarrow \text{False}$ 
2: if there are peer caching nodes  $\zeta$ ,  $F_p = 1$ , then
3:   if (requester,  $v_u$ , is in  $FC$ ,  $v_u \in \zeta$ ) and ( $v_u$  has content  $k$ ) then
4:      $id_s \leftarrow u$ ,  $F_s \leftarrow \text{'r'}$ ,  $CacheHit \leftarrow \text{True}$ 
5:   else
6:     while  $CacheHit \leftarrow \text{False}$  do
7:       for all every peer caching node  $v_i$  in  $\zeta$ ,  $v_i \in \zeta^{(0)}$  and  $v_i \neq v_u$  do
8:         Forward request message  $m_k^u$  from  $v_u$  to  $v_i$ 
9:         if  $v_i$  has the requested content  $k$  then
10:            $id_s \leftarrow i$ ,  $F_s \leftarrow 0$ ,  $CacheHit \leftarrow \text{True}$ 
11: return  $id_s$ ,  $F_s$ ,  $CacheHit$ 
```

Two important variables, the serving flag and the serving node id, are introduced in algorithms 4-6. The serving flag, F_s , is used to record the tier number, where the content is ultimately found. It can either take an integer value from $\{0 \dots max\}$ to indicate the tier t value, or the value 's' (source), if the content is found at the original source. Lastly, if the content is located at the requesting node itself, in case the content was previously cached there, the F_s flag will take the value 'r' (requester). In addition, once the content is found in a caching node, the serving node id variable, id_s , simply stores the id number of the node that holds and serves the content. This information will be later used in the content caching process.

Alg. 4 searches for the requested content both within the requesting node itself, v_u , and all of its peer nodes, v_i . Initially, the requesting node checks whether itself holds the content. If it does, then the id_s value is assigned with the ID u of user v_u and the serving flag F_s is assigned to 'r' to represent a local cache hit (lines 3-4). Otherwise, if the cache of requested content k cannot be found locally, the request is forwarded to all the other nodes, v_i , in $C^{(0)}$, until a cache hit occurs (lines 7-8). When a cache hit

Algorithm 5 Request message routing & delivery to original content provider

Input: Serving flag F_s , requesting end-user device v_u , requested content k , original content provider v_{pk} , $FC \mathcal{C}$, peer flag F_p , boolean value $CacheHit$

Output: Serving node ID id_s , serving flag F_s

- 1: **if** ($CacheHit = \text{False}$) and ($C^{(1)}$ is $\emptyset$) **then**
 - 2: Forward request message m_k^u from requester v_u to original content provider v_{pk}
 - 3: Retrieve the requested content k from provider v_{pk}
 - 4: $id_s \leftarrow pk, F_s \leftarrow 's'$
 - 5: **return** id_s, F_s
-

occurs, id_s is assigned the id of the node v_i and F_s is set to '0' to indicate a zero-tier peer node cache (line 9).

360 If a cache hit has not occurred within tier 0 (therefore the serving flag is not set) and there are no caching nodes in higher tiers, i.e. $C^{(1)} = \emptyset$, the request message is forwarded directly from user v_u to the original content source v_{pk} , as shown in Alg. 5 (lines 1-2). Once the content is received from the content provider, the serving flag F_s and the id_s are assigned with 's' and the ID of the content provider, pk , respectively (lines 3-4).

365 Alternatively, if a serving cache node has not been found yet, $CacheHit = \text{False}$, and there are caching nodes in higher tiers, $C^{(1)} \neq \emptyset$, the request message m_k^u would be traversed from the lowest to the highest tiers in search of a cache hit, as shown in Alg. 6. If F_p is 1, it means there is peer cache in $\mathcal{C}$ and, therefore the Bottom cache node exists in tier 0. In this case, the v_{Bottom} node has already obtained the request message during the peer searching process (Alg. 4) and is not part of Alg. 6.

375 Otherwise, if F_p is 0 (line 2), message m_k^u is forwarded from v_u to the Bottom cache node v_{Bottom} . In the first tier traversing, the request message m_k^u is broadcasted from v_{Bottom} to all the nodes in the first tier nodes in sequence (lines 5-11). If a cache hit occurs, the id_s would record the provider ID and F_s is set to 1, representing that a cache hit occurred in the first tier. In this case, the request routing and delivery process is finished and the content delivery and caching process in step 3 would be triggered.

Nevertheless, if there is no cache hit in the first tier, the last traversed node in the first tier is set as a temporary gate, v_g , tasked to broadcast the request message to the next tier (lines 13). Similarly, if there is no cache hit, the request message is recursively
380 delivered to each higher tier (lines 15-23). Once the highest, max , tier is reached and, still, there is no cache hit, then the request is routed from v_{up} to the original content provider v_{pk} (lines 24-27).

Algorithm 6 Request message routing & delivery in FC Tiers ≥ 1

Input: Serving flag F_s , requesting end-user device v_u , requested content k , original content provider v_{pk} , FC ζ (including v_{Bottom}), peer flag F_p , boolean value $CacheHit$

Output: Serving node ID id_s , serving flag F_s

```
1: if ( $CacheHit = \text{False}$ ) and ( $\zeta^{(1)} \neq \emptyset$ ) then
2:   if there is no peer cache in  $\zeta$ ,  $F_p = 0$ , then
3:     Forward request message  $m_k^u$  from requester  $v_u$  to Bottom cache node  $v_{Bottom}$ 
4:   while  $CacheHit \leftarrow \text{False}$  do
5:     for all node  $v_i$  in the first tier of  $\zeta^{(1)}$ ,  $v_i \in \zeta^{(1)}$  do
6:       if ( $v_i$  is  $v_{Bottom}$ ) and ( $v_i$  has the requested content  $k$ ) then
7:          $id_s \leftarrow i$ ,  $F_s \leftarrow 0$ ,  $CacheHit \leftarrow \text{True}$ 
8:       else if ( $v_i$  is not  $v_{Bottom}$ ) and ( $CacheHit = \text{False}$ ) then
9:         Forward request message  $m_k^u$  from  $v_{Bottom}$  to  $v_i$ 
10:        if  $v_i$  has requested content  $k$  then
11:           $id_s \leftarrow i$ ,  $F_s \leftarrow 1$ ,  $CacheHit \leftarrow \text{True}$ 
12:   if  $CacheHit = \text{False}$  then
13:     Initialise the last searched node as the gateway to next tier, tier 2,  $v_g \leftarrow i$ 
14:   while  $CacheHit \leftarrow \text{False}$  do
15:     for all tier  $t$  existing between 2 and  $max$  do
16:       if  $CacheHit \leftarrow \text{False}$  then
17:         for all node  $v_n$  in the  $\zeta^{(t)}$ ,  $v_n \in \zeta^{(t)}$ , do
18:           Forward request message  $m_k^u$  from  $v_g$  to  $v_n$ 
19:           if  $v_n$  has the requested content  $k$  then
20:              $id_s \leftarrow n$ ,  $F_s \leftarrow t$ ,  $CacheHit \leftarrow \text{True}$ 
21:         else
22:            $CacheHit \leftarrow \text{True}$ 
23:         Assign the last searched node as the gateway to next tier, tier  $(t+1)$ :  $v_g \leftarrow v_n$ 
24:   if  $CacheHit = \text{False}$  then
25:     Forward the request  $m_k^u$  from the highest tier gate  $v_g$  to content original provider  $v_{pk}$ 
26:     Retrieve the requested content  $k$  from provider  $v_{pk}$ 
27:      $id_s \leftarrow pk$ ,  $F_s \leftarrow 's'$ 
28: return  $id_s$ ,  $F_s$ 
```

Algorithm 7 Content Delivery and Reactive Caching

Input: Serving flag F_s , serving node ID id_s , requesting end-user device v_u , requested content k , original content provider v_{pk} , FC ζ (including v_{Top})

Output: None

- 1: **if** (F_s is 's') and ($\zeta \neq \emptyset$) **then**
 - 2: Deliver content k from original v_{pk} to Top cache node v_{Top}
 - 3: Put content k into Top cache node v_{Top}
 - 4: Forward content k from v_{Top} to v_u
 - 5: **else**
 - 6: Forward content k from serving node v_{id_s} to v_u
 - 7: **return** None
-

5.3. Step 3 Content Delivery and Caching

385 Once the requested content is found in any of the above cases (tier 0, tier ≥ 1 , or original source), the content is delivered back to the requesting user whilst a cache of the content is stored within the FC , following either a reactive and/or a proactive caching scheme. This step is powered by the full-time caching attribute of the proposed scheme.

390 Once the requested content k is delivered back to user v_u , a reactive caching strategy would leave a single cache k in the FC . The proactive caching process will then populate the FC with additional content caches. Specifically, as shown in Alg. 7, only when the content is found in the original content provider ($F_s = \text{'s'}$) and there are nodes in the Fog-Cluster ($\zeta \neq \emptyset$) (line 1), is reactive caching activated to leave a cache in v_{Top} (lines 2-4). In this case, a duplicate of content k is firstly forwarded to the Top cache node, v_{up} (line 2). Once the content is cached in v_{up} , it is forwarded back to user v_u (lines 3-4).

400 Regarding the proactive caching operation in Alg. 8, if there is a caching node existing in the FC and the content request has been satisfied by the original content provider ($F_s = \text{'s'}$), a cache should already exist in the Top cache node, from the reactive caching process. In this case, the content is redistributed from v_{Top} to all the caching

nodes in the highest tier caches (lines 2-5). If the highest tier is the end-user tier, an additional content is cached in the user device v_u , if it has caching character (lines 6-7).

If the v_{id_s} is the caching node in any tier $t \geq 2$, the requested content is moved
 405 to caches located at one tier lower ($F_s - 1$). In this case, the contents in tier F_s are removed to reduce the caching redundancy (lines 8-13). In addition, if the receiver device has caching character, another content is leaved there as well (lines 14-15) In another case, if there is peer cache existing in ζ and v_{id_s} is one of peer caches ($F_s = 0$), the content should be forwarded from the serving peer cache to user v_u (line 18-19).

410 6. Experimental Set Up

In order to evaluate the proposed in-network caching scheme without binding to any specific ICN architecture, the caching simulator Icarus [11] is chosen to conduct the experiments, running on an Intel Core i5-4200M at 2.5Ghz, 4 core CPU with 4GB of RAM.

415 In this section, a suitably designed topology for Fog caching evaluation purposes is provided. The parameter configuration, topology design and performance metrics are elaborated in the following subsections.

6.1. Simulation Parameters

In our simulation, the parameters could be categorized into three groups, which are
 420 request message parameters, content parameters and caching parameters. The detailed configuration in these three categories are successively explained as follows.

The request message parameters involve the arrival distribution, generation rate and Icarus' warm up and measured messages. The warm up messages are traffic generated in the initial phase to populate the caching nodes with cached contents. Whereas the
 425 measured messages are the actual request messages collected for evaluation purposes once the warm up phase finishes.

The request message arrival is following the Poisson distribution, which is the most widely used distribution in conventional caching experiments [43, 44]. The content generation rate is set to 12 request messages per second, since this is Icarus' default

Algorithm 8 Content Deliver & Proactive Caching

Input: Serving flag F_s , serving node ID id_s , requesting end-user device v_u , requested content k , FC ζ (including v_{Top}), peer flag F_p

Output: None

```
1: if ( $F_s$  is 's') and ( $\zeta \neq \emptyset$ ) then
2:   for every  $v_i$  in highest tier cache,  $v_i \in \zeta^{(max.)}$  do
3:     if  $v_i$  is not  $v_{Top}$  then
4:       Deliver content  $k$  from Top cache node  $v_{Top}$  to  $v_i$ 
5:       Put content  $k$  into caching node  $v_i$ 
6:   if ( $max$  is 0) and ( $v_u$  has caching character,  $v_u \in C$ ) then
7:     Put content  $k$  into requester  $v_u$ 
8: if the serving node is in tier  $\geq 2$  and  $F_s$  exists between 2 and  $max$  then
9:   for every  $v_i$  in tier  $(F_s - 1)$ ,  $v_i \in \zeta^{(F_s-1)}$ , do
10:    Deliver content  $k$  from  $v_{id_s}$  to  $v_i$ 
11:    Put content  $k$  into  $v_i$ 
12:   for every  $v_x$  in tier  $F_s$  tier,  $v_x \in C^{F_s}$  do
13:     Remove content  $k$  from  $v_x$ 
14:   if ( $v_u$  has caching character,  $v_u \in C$ ) then
15:     Put content  $k$  into  $v_u$ 
16: if ( $F_s$  is 0) and ( $F_p$  is 1) then
17:   if ( $v_u$  has caching character,  $v_u \in C$ ) then
18:     Deliver content  $k$  from  $v_{id_s}$  to  $v_u$ 
19:     Put content  $k$  into  $v_u$ 
20: return None
```

430 setting and does not negatively impact the performance of the host machine running the simulations. In addition, the other two request parameters, i.e. the number of warm up messages and measured messages, are configured as 3×10^5 and 6×10^5 messages, respectively.

Content parameters consist of number of contents, $|K|$, and content popularity parameter, α . The number of contents varies considerably depending on the simulated 435 scenario. For example, the number of contents pertaining to user generated videos would be much larger than in video-on-demand scenarios. In our experiments, the number of contents is 3×10^5 individual contents. Zipf's law, $\frac{1}{|K|^\alpha}$, conventionally employed in related work, is chosen for the content popularity distribution. The α 440 parameter in Zipf's law reflects the concentration of user preference and ranges from 0.75 to 1.25 in the experiments. The greater the α value is, the more concentrated the user preference is. In other words, assuming $\alpha = 1.25$, more request messages are asking for the same content than if $\alpha = 0.75$.

For the third parameter category, caching parameters include network caching capacity, storage capacity allocation and content eviction algorithm. For fairness purposes, the sum of storage capacity of caching nodes in different topologies should be consistent. Therefore, network caching capacity (CC) is set as a constant value for all topology scenarios. This constant value denotes the ratio of total network caching capacity over number of contents, $|K|$, as in Eq. 1.

$$CC = \frac{1}{|K|} \sum_{c_i \in C} |c_i|, \quad (1)$$

where c_i is the caching capacity of node i .

445 In this work, the network caching capacity ranges from 0.2% to 5%. Under the uniform capacity allocation scheme, the storage capacity of all caching nodes is equal. Therefore, the caching capacity of each caching node is the ratio of CC over the number of caching nodes. Regarding the used content eviction algorithm, the proposed scheme implements the LRU, which has a constant time complexity, but also keeps 450 the consistency with most of existing ubiquitous caching schemes. Based on the above request, content and caching parameters, each analysed caching scheme is analysed with 10 possible values for network caching capacity and 11 different α values for content

Parameters	Configuration
Request arrival	Poisson's Distribution
Request rate	12 requests per second
Num. of warm up request	3×10^5 messages
Num. of measured request	6×10^5 messages
Num. of contents	3×10^5 contents
Content popularity	Zipf's law, $\alpha = 0.75, 0.8, \dots, 1.25$
Network caching capacity (CC)	0.2%, 0.6%, 1%, 1.4%, 1.8%, 2.2%, 2.6%, 3%, 4%, 5%
Storage capacity allocation	Uniform
Content eviction algorithm	Least Recently Used (LRU)
Num. of iterations for each experiment	3
Performance metrics	Latency, Cache Hit Ratio, Internal Link Load, Path Stretch

Table 3: Experimental set-up parameters and configuration.

popularity, as shown in Table 3, thus, composing 110 scenario configurations in total. Each evaluated scenario is iterated three times and the average value for each metric is calculated and used for comparison purposes against benchmark caching schemes. The simulation configuration is summarised in Table 3.

6.2. Topology Configuration

Although many research works are focusing on Edge or Fog caching, there is lack of appropriate topology consideration for Fog caching evaluation purposes. The conducted experiments aim to address a lack in related work by simulating IoT scenarios at network Fog, which exhibiting request traffic for both user generated and conventional, on-demand content. In addition, the evaluated topologies in other related works are either small scale and coupled to specific network technologies [45, 46] or large scale based on an existing backbone topology [47, 48] that is not appropriately structured to simulate a Fog environment. To this end, a novel simulation topology is proposed, which includes user devices that not only send requests, but also participate as caching nodes and may

even provide user generated content. In addition, ICN routers, traditional forwarding nodes, and content providers in core network are also included in the topology design.

Specifically, the design of our topology is based on a traditional tree structure as shown in Fig. 2. The root node, v_9 , represents the core network, where there is an original content source located. The children of the root are the cloud-edge nodes, v_7 and v_8 , which are connected to the Fog's outer edge, i.e. the highest caching tier in FC . Since the hops between the Fog's outer edge and cloud-edge do not take responsibility in the proposed Fog-based scheme, they are not utilised in our topology implementation. At the Fog, ICN nodes v_3 - v_6 are connected with access points v_1 and v_2 at network edge, each of them have both caching and forwarding characters. For v_1 and v_2 , they are connected to several user-devices with allocated end-user characters, as described in Section 4.1.

In our experimental topology, there are six end user devices and all of them have caching character. Since there are user generated contents in IoT environment, two of the available user devices are also assigned with content source character. Besides, to place more emphasis on the network fog, the potential bottleneck at the core network is eliminated by assigning unlimited bandwidth for those links during the simulations. Thus, any delay would be caused by the Fog node links, rather than the backbone.

6.3. Performance Metrics

There are four metrics used for performance evaluation, which are latency (LAT), cache hit ratio (CHR), internal link load (LL_{in}) and path stretch (PS). The definitions of these metrics are described as follows, [11]:

Latency: Mean latency is the average delay from each request m_k^u generated until the content k is delivered to the user v_u . The amount of measured requests are denoted by the size of request set $|M|$, generated during the simulation time T . In order to calculate the delivery delay of request m_k^u , $DEL(m)$, the forwarding operations of both request message, m , and content objects, o , for request m_k^u are collected in sets $F(m)$ and $F(o)$,

respectively. Then, the deliver delay of message m is given by Eq. 2:

$$DEL(m) = \sum_{(v_a, v_b) \in F(m)} d(v_a, v_b) + \sum_{(v_a, v_b) \in F(o)} d(v_a, v_b), \quad (2)$$

495

where the link delay between node v_a and v_b is denoted as $d(v_a, v_b)$.

Finally, the latency LAT metric is defined as the average delivery delay of message m , as in Eq. 3.

$$LAT = \frac{1}{|M|} \times \sum_{m \in M} DEL(m) \quad (3)$$

Cache Hit Ratio: The cache hit ratio metric is a portion of the requests satisfied by caching nodes, rather than servers. Let us assume that there are M request messages being served in total and the session providers are either content sources or Fog-caches. If a cache of requested content k can be found in one of the Fog nodes in FC , a cache hit is added in counter H_c . On the other hand, if m can not be satisfied within the FC , it will be served by the original content source, and this is counted as a server hit H_s . Therefore, the cache hit ratio is defined in Eq. 4,

$$CHR = \frac{H_c}{H_s + H_c} = \frac{H_c}{|M|} \quad (4)$$

Internal Link Load: The internal link load (LL_{in}) is the average traffic load of links at the network Fog. Let m be the message size of each request and o_k be the content size of requested object k . In Icarus, the content size are uniform, so the size of content object can uniformly be denoted as o . The amount of contents and requests passed by link e are represented by $N_o(e)$ and $N_m(e)$, respectively. The link load of link e is denoted as LL_e , which is defined as Eq. 5:

$$LL_e = \frac{1}{T} [|m| \times N_m(e) + |o| \times N_o(e)] \quad (5)$$

Moreover, let E_{in} be the set of internal links in the Fog topology. The mean internal link load for the used links LL_{in} in the Fog topology is calculated as shown in Eq. 6.

$$LL_{in} = \frac{1}{|E_{in}|} \sum_{e \in E_{in}} LL_e \quad (6)$$

Path Stretch: Path stretch (PS) is the metric reflecting the length of delivery path. In the ubiquitous caching scenario, the closer to the requesting node the cache hit happens, the lower the PS value is. Specifically, PS is the ratio of the total length of delivery path over the length of shortest routing path between user v_u and v_{pk} . The length of shortest path between nodes a and b is denoted as $SP(a, b)$. The path stretch of request message PS_m and content object PS_o is defined in Eq. 7 and 8, respectively. The PS uses the average path stretch value of request messages and content objects.

$$PS_m = \frac{1}{|M| \times |SP(v_u, v_{pk})|} \sum_{m \in M} \sum_{(v_a, v_b) \in F(m)} |SP(v_a, v_b)| \quad (7)$$

$$PS_o = \frac{1}{|M| \times |SP(v_{pk}, v_u)|} \sum_{m \in M} \sum_{(v_a, v_b) \in F(o)} |SP(v_a, v_b)| \quad (8)$$

$$PS = \frac{PS_m + PS_o}{2} \quad (9)$$

7. Results and Discussion

For comparison evaluation, eight caching schemes are chosen as benchmarks, which are Edge Caching, Consumer Caching (CSM), LCE, LCD, RAND, CL4M, Random
500 Bernoulli and ProbCache. In particular, Edge Caching and CSM are popular schemes focusing on caching node placement. Edge Caching caches the content in distributed caching hops located at the network edge, e.g. proxy servers for content delivery network (CDN). CSM caches popular contents locally in end-user devices. LCE and LCD are two classic content placement strategies for ubiquitous ICN caching. The former one
505 cache the requested content to all the caching hops on the delivery path, while the latter one moved the cached content towards the end-users hop-by-hop along the delivery path when the content is repeatedly requested. In random-based content placement, RAND caches content in a randomly selected caching node on the delivery path, while Random Bernoulli randomly inserts content in an on-path node with probability p [11]. CL4M,
510 a more recent caching scheme is based on graph-based centrality [13]. ProbCache

calculates the probability of caching specific content according to a node’s position and remaining caching space on the delivery path [14].

In the conducted 110 experiments discussed earlier, four of the benchmark schemes, LCE, CL4M, Edge Caching and CSM, present comparable performance for the evaluation metrics of latency, cache hit ratio and path stretch. A sample representation of these results is presented in Table 4. It is worth noting that for the internal link load metric, CSM performs better than the rest of the schemes. This is justified because the CSM scheme caches content at the user side, thus, resulting in the lowest link load results, as seen in Table 4. For this reason, CSM is chosen as the representative benchmark among these four schemes. However, the remaining four schemes, LCD, RAND, Random Bernoulli and ProbeCache, vary significantly and are preserved in the following comparison results.

7.1. Cache Hit Ratio

The cache hit ratio is one of the most important metrics among the four investigated in our evaluation, because a high cache hit ratio implies a reduced workload at the core network and balances the content requests among the available cache resources. Conventionally, a high cache hit ratio implies that the content requests are satisfied by nearby caching nodes, rather than the remote original content source, thus incurring a low latency along with low link load and short path stretch. The proposed scheme performs consistently better in comparison to the five benchmarks in all the conducted

Caching Scheme	Latency	Int. Link Load	Cache Hit Ratio	Path Stretch
LCE	83.643 (ms)	1948.545 (bytes)	43.1%	54.2%
CL4M	84.214 (ms)	1947.037 (bytes)	42.7%	54.8%
Edge Caching	84.264 (ms)	1945.853 (bytes)	42.7%	54.4%
CSM	82.605 (ms)	1419.158 (bytes)	42.6%	45.9%

Table 4: Performance results for LCE, CL4M, Edge Caching and CSM with content popularity skewness $\alpha = 1$ and network caching capacity $CC = 3\%$. These four schemes perform similarly in all metrics with the exception of internal link load for CSM.

Figure 3: Cache Hit Ratio of proposed scheme against benchmark schemes.

experiments where the skewness and CC parameters vary across all examined values, as shown in Table 3. Fig. 3a and Fig. 3b show the cache hit ratio performance of all analysed schemes with varying caching capacity (CC) and fixed content popularity skewness, α , equal to 0.75 and 1.25, respectively. On the other hand, Fig. 3c and Fig. 3d plot the cache hit ratio performance for all six caching schemes under varying α values, but with CC equal to 0.2% and 5%, respectively.

Generally, in all the evaluated scenarios, the average cache hit ratio of the proposed scheme is 51.8%, which is 4.9% higher than the second best scheme, i.e. LCD (with an average cache hit ratio of 49.4%). As shown in Fig. 3a, the cache hit ratio of the proposed scheme improves by up to 2.7% in comparison to LCD. In Fig. 3b, where α = 1.25, the cache hit ratio has a slight improvement ranging between 1.4% and 2.8%, in comparison to LCD.

The adjustable FC attribute of the proposed scheme, allows the possibility for end-user devices to act as content caching nodes and serve their neighbours while being in a close proximity. This is one attribute that justifies the better performance of our scheme. However, as it is observed from the Consumer Caching scheme, which is solely based on end-user caching, its performance is less than the proposed scheme under the considered topology. The reason why the proposed scheme succeeds in achieving a higher cache hit ratio performance is because in addition to utilising end-user devices, it also adopts the near-path caching that leverages available caching resources close to the delivery path. It is also worth mentioning that when the content preference becomes less concentrated, i.e. users request a wider variety of content (see Fig. 3a), then there is an increasing impact to the performance of the proposed scheme with increasing CC , in comparison to when the content preference is more concentrated (see Fig. 3b).

Figures 3c and 3d show that with increasing α and fixed CC the cache hit ratio performance changes roughly from 10% to 70% and from 20% to 85%, respectively. This performance change is significantly larger than the performance gains achieved when varying the CC values and having fixed α values, shown in Figures 3a and 3b. Therefore, the selection process for a caching scheme should mainly be based on the particular content popularity skewness within the Fog network.

Figure 4: Latency performance of the proposed scheme against benchmark schemes.

7.2. Latency

The latency of the six caching schemes is shown in Fig. 4. The average latency of the proposed scheme is 75.78ms, which is just 1.2% higher than LCD (74.85ms) and 1.8% lower than the third best scheme, ProbCache (77.13ms). Specifically, Fig. 4a - 4c show the latency fluctuating against the network CC with a fixed content popularity parameter α . In contrast, Fig. 4d - 4f illustrate the oscillation of latency against the popularity parameter α with the certain network CC . Generally, when the network CC increases, the latency is naturally decreased because more contents could be cached in the network. In addition, when the user preferences become concentrated (α value is large), the latency of all the caching schemes is decreased as well.

In particular, among the selected caching schemes, our proposed scheme can achieve lower latency when the α value is greater than 1. In this case, the content requests are concentrated towards a specific range of content. Since the proposed scheme is utilising caching resources near the end-user's path, this will incur a performance benefit to other end-users in the surrounding network. In other words, the caching efficiency increases when the content popularity is concentrated for α values larger than 1. This is illustrated in Fig. 4c, when α is 1.15, and the proposed scheme outperforms the rest benchmarks. Nonetheless, when the user preferences are dispersing, i.e. α values is less than 1, as seen in Figures 4a and 4b, the latency performance of the proposed scheme is significantly improved with increasing network CC in comparison to the remaining schemes. Specifically, in Fig. 4a, when $\alpha = 0.75$, the proposed scheme has large delay, around 145 ms, when network CC is lower than 1%. When CC is between $1\% \leq CC < 5\%$, the proposed scheme can achieve lower delay than RAND, Random Bernoulli and CSM, reaching the performance of ProbCache, but not as low as that of LCD.

A potential disadvantage of the near-path attribute is that when the content popularity is disperse, instead of searching for available caches only on the delivery path, as LCD and ProbCache do, the near-path attribute will have to incrementally search every node within each tier until a cache hit. This is incurring an increased latency from the onset of the content request until it is satisfied.

Figure 5: Internal Link Load of the proposed scheme against benchmark schemes.

7.3. Link Load & Path Stretch

Figures 5a and 5b show the internal link load performance against a varying skewness parameter for a fixed value of CC equal to 0.2% and 5%, respectively. In both situations the proposed scheme performs significantly better compared to the five benchmarks. This is a direct result of the full-time attribute that diverts the request traffic load outside the peak time period.

The average internal link load performance of the proposed scheme for all evaluated scenarios is 1084.72 bytes, which is 27.9% better than the second best scheme, CSM with an average of 1505.17 bytes. This reduction in link load happens due to the fact that the proposed scheme caches the content in the end-user devices. In particular, when the user preference is disperse (i.e. $\alpha = 0.75$ in Fig. 5a), the internal link load of the proposed scheme is 1944.52 bytes and that of CSM is 2440.97 bytes. This results in a 20.3% improvement for the proposed scheme. When α increases to 1.25, the internal link load of the proposed scheme is 606.97 bytes and that of CSM is 1012.89 bytes, which results in a 40.1% improvement for the proposed scheme. Similarly, when $CC = 5\%$ (Fig. 5b), the internal link load improvement against CSM ranges from 24.6% up to 35.1%.

The internal link load of ProbCache, RAND, Random Bernoulli and LCD greatly

Figure 6: Path Stretch indicates a significant gain for the proposed scheme in comparison to benchmarks.

under-perform in the majority of the evaluated scenarios. In most scenarios, CSM
 610 achieves a lower link load than LCD. Interestingly, when both α is less than 1 and CC
 around 0.2%, LCD can attain slightly lower internal link load than CSM, as seen in
 Fig. 5a. This happens because, when the user preferences are dispersing, the end-user
 device cannot cache the highly requested content within a limited caching capacity.

Finally, the experimental results for path stretch against varying CC and α are
 615 shown at the left and right sides of Fig. 6, respectively. These are two representative
 examples from all 110 simulations and clearly highlight that the proposed scheme can
 significantly reduce the path stretch, due to the near-path approach. The reason for this
 is that when popular content is re-hit, it is gradually moved from higher to lower tiers,
 closer to the end-users. Thus, the delivery path of content is drastically reduced.

620 As shown in Fig. 6a, as CC increases from 0.2% to 5%, the reduction of PS achieved
 by the proposed scheme ranges from 3.3% up to 7.3% in comparison to the second best
 scheme, LCD. In addition, as shown in Fig. 6b, when α increases from 0.75 to 1.25,
 the path stretch of the proposed scheme ranges from 8.6% to 4.3% in comparison to
 this case's second best scheme, CSM.

625 8. Conclusions and Future work

This paper identifies six important design drivers of conventional ICN schemes by critically examining the state-of-the-art. After a thorough consideration of the six design drivers, a novel Fog caching scheme is proposed to efficiently facilitate content delivery in IoT environments. The proposed scheme is enabled both by the in-network
630 caching capability of ICN, but also of end-user devices.

The proposed scheme leverages available information on node capabilities, such as forwarding, peer caching and content generation characteristics, as well as the tier-based locality within the Fog topology. By doing so, the scheme is able to construct adjustable sizes of clusters that efficiently provision caching within a Fog network. The caching
635 nodes in the same Fog-Cluster work collaboratively to serve a group of end-users, that compose their respective user clusters.

In addition, this work introduces the near-path and full-time caching concepts. The former is an approach inspired by the on-path/off-path schemes, whilst the latter is a carefully designed hybrid between the reactive/proactive caching schemes. Specifically,
640 the Fog caching nodes near the delivery path are identified that may efficiently reduce the content delivery latency and traffic load, as well as increase the cache hit ratio in Fog networks. Compared to traditional on-path/off-path schemes, the unique near-path design is more suitable to IoT scenarios in which the data are mainly generated and requested at the network edge. In addition, the full-time feature performs both a
645 reactive and proactive caching, only if the requested content is found at the original source, otherwise it only performs proactive caching to avoid creating congestion during the peak-time.

Thus, by incorporating three key attributes: flexible and adjustable node clustering, near-path content allocation and full-time caching, the six design drivers are satisfied. Experiments are conducted using a bespoke Fog topology running in the Icarus sim-
650 ulation environment, where content is located in both the core network, as well as, in end-user nodes. The experiments show that the proposed scheme design can achieve outstanding performance with this mixture of content generation. The proposed scheme is implemented and evaluated against Edge Caching, LCE, CL4M, CSM, ProbCache,

655 LCD, RAND and Random Bernoulli caching schemes.

The experimental results clearly show that the cache hit ratio performance of the proposed scheme is always better than the benchmarks, especially when the network caching capacity increases towards 1%. The latency performance of Fog caching is affected both by the content popularity and the caching capacity. In fact, the proposed
660 scheme achieves lower latency compared to most popular caching schemes when the user preference dispersion, α , is less than 1%). Finally, on average, in terms of internal link load and path stretch, the proposed scheme achieves an improvement of 27.9% and 8.5%, respectively.

In this work, user-devices and Fog caching nodes are organised into clusters de-
665 pending on their capabilities and topological position. In future work, further criteria, such as content preference of users, geographical distribution and caching capacity, are expected to be considered during a node's cluster assignment. In addition, real-time design adjustments may be investigated depending on the network conditions and context. Finally, larger scale of experiments could be further considered.

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