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PAPER

Caching Strategies for the Metaverse: Taxonomy, Open Challenges, and Future Research Directions

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ABSTRACT

The metaverse, which is considered to be the next evolutionary stage of the Internet, has captured the attention of both academia and industry. Its primary goal is to establish a shared 3D virtual space that interconnects all virtual worlds through the Internet. In this shared space, users are represented as digital avatars, enabling them to communicate, interact with each other, and engage with the virtual environment as if they were in the physical world. However, realizing the full potential of the metaverse poses significant challenges, such as the requirement for higher throughput compared to current social VR platforms and the need to minimize latency to just a few milliseconds to uphold a truly immersive user experience. Caching is a critical aspect of optimizing data access on the current Internet, and it is equally crucial for addressing similar challenges in Web 3.0 and the metaverse. This paper explores different caching strategies suggested to address these challenges on the current Internet and assesses their potential relevance to the metaverse. Caching strategies are categorized into three groups: web caching, mobile caching, and Internet of Things (IoT) caching. Recent solutions are then examined to determine their relevance to the metaverse. Finally, the paper discusses open research challenges and potential future research directions in this domain.

KEYWORDS

metaverse, Web 3.0, caching strategies, mobile caching, Internet of Things (IoT) caching

1 INTRODUCTION

The ever-growing demand for computation-intensive applications, especially within the metaverse context, has prompted the search for groundbreaking solutions. Network computing (COIN) is emerging as a promising paradigm to harness the untapped potential of existing network resources to solve the challenges presented by these computation-demanding applications [1]. The metaverse represents an undefined frontier of Internet applications and social interaction that seamlessly integrates a wide range of advanced technologies [2]. It possesses defining features,

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including multi-technology integration, a strong sense of social connectivity, and hyper-spatiotemporality. As the next-generation Internet paradigm, the metaverse's primary objective is to deliver 3D immersive experiences and establish self-sustaining virtual shared spaces by leveraging a wide spectrum of relevant technologies [3]. At its core, the metaverse aims to construct an immersive virtual world that enables users to interact and collaborate in real-time, both with one another and the digital environment, utilizing their virtual reality (VR) headsets. This concept of the metaverse embodies a host of distinctive features, including immersiveness, sustainability, interoperability, decentralization, safety, and trustworthiness [4]. To achieve these remarkable characteristics, the metaverse integrates and leverages various innovative technologies, such as 5G mobile communication, extended reality (XR), blockchain, machine learning, human-computer interaction, and edge computing.

The metaverse has captured widespread attention from the public, academia, and industry, attracting substantial investments from prominent technology companies. However, realizing the full potential of the metaverse requires addressing numerous fundamental challenges [5]. One critical concern in developing fully decentralized metaverse platforms is efficiently transmitting 3D multimedia content to users' devices and dynamically downloading relevant environments as they traverse between different virtual worlds [6]. The metaverse contains an enormous volume of multimedia content, making it necessary to employ various multimedia techniques, such as compression and coding methods, in order to enhance network communication for metaverse applications [7]. Despite the progress made, significant issues persist. One of the foremost challenges is meeting the demand for higher throughput compared to current social VR platforms, as well as achieving latency as low as ten milliseconds to maintain an optimal and immersive user experience [8]. These issues continue to be major hurdles in the realization of high-quality and truly immersive experiences.

The metaverse is often referred to as the next-generation Internet, representing an extension of web-based interaction from the traditional 2D web to a more immersive 3D web, essentially becoming the browsers of the future. Given this transformation, it becomes crucial to examine existing caching strategies that have played significant roles in the current 2D web and explore their potential applications in the metaverse context. Specifically, we should study web caching, mobile caching, and Internet of Things (IoT) caching as they pertain to the metaverse.

As the metaverse undergoes further development, the importance of caching grows in tandem with the progressions in information theory [9]. Notably, during the same year when Netflix experienced an unprecedented fourfold increase in the value of its shares, a seminal work on caching was introduced on arXiv [10]. The essence of caching lies in its ability to alleviate network load caused by on-demand video streaming. This is achieved through proactive data caching based on anticipatory demand prediction.

The key to optimizing caching in the metaverse lies in the development of efficient and accurate demand prediction algorithms. These algorithms are tasked with anticipating users' preferences and preemptively storing the relevant data in the cache, ensuring its availability when subsequently requested. By successfully predicting and caching the data that users are likely to require, network resources can be utilized more effectively, leading to improved performance and enhanced user experiences within the metaverse.

The significance of effective cache management and its potential benefits, such as reducing network load and improving the user experience, highlights the need for collaboration among communication engineers, data scientists, and other stakeholders [11], [12]. The text mentions two phases: anticipating demand and responding to real-time data requests, emphasizing the importance of updates over content delivery.

It also discusses the trade-off of eliminating unnecessary cached information and the continuous quest for techniques to decrease communication rates [13]. It delves into lossy source coding in database modeling and its correlation with previous research [14]. The text refers to a model revision that incorporates a lossy scenario, emphasizing caching strategies for both overall performance and individual user data preferences [15].

The cache encoder is influenced by user file preferences and file relationships, broadcasting initial messages compared to update messages sent upon file requests [16]. It mentions the influence of user preferences on caching and references related research [17], [18]. Two examples are Watanabe's complete correlation [19]. User preference and caching have no effect on each other. In line with this consideration, a study closely related to this issue is the research conducted by T. Trinh et al. [20].

In order to decrease latency and enhance the user experience, edge caching is a specific type of caching that is performed at the edge of the network, closer to the end user. Edge caching can be utilized to store frequently accessed data at the network's edge in the context of databases, reducing the necessity for constant connection with the primary database and improving system performance. Caches often retain a subset of data while it is in transit, whereas databases generally store more comprehensive and permanent data.

There are three key components of a web caching system: the cache, the origin server, and the client. The cache plays a crucial role as temporary storage for frequently accessed content and is responsible for checking for the requested content. If the cache has the content, it delivers it to the client; if not, it fetches the data from the origin server, stores it, and then transmits it to the client.

The main objectives of this research are to investigate the current associated with designing and the metaverse and to identify significant knowledge gaps in this area. A thorough review of the literature served as the foundation for conducting a systematic mapping study with the aim of achieving this goal within the context of the metaverse. The study will address the following research questions:

1. How will caching impact web application performance in the context of the metaverse?
2. What are the primary caching strategies used in web applications and mobile caching?
3. What are the main research works and advancements in IoT caching and their implications for the metaverse?
4. What are the key challenges and open issues in designing effective caching mechanisms for the metaverse?

With regard to the aforementioned questions, we reviewed a number of thoughtfully selected journal articles and developed a classification schema to group the challenges and unresolved problems associated with the creation of metaverse content. To clearly grasp the identified obstacles and unresolved concerns, the study's findings are analyzed in detail. Based on the findings, suggestions are made for further investigation in this area. In the organization of this paper, we delve into various aspects of caching technologies. Section 2 discusses web caching, while Section 3 focuses on mobile caching. Section 4 explores the realm of IoT caching, and finally, in Section 5, we address the open research challenges in this domain (see Figure 1).

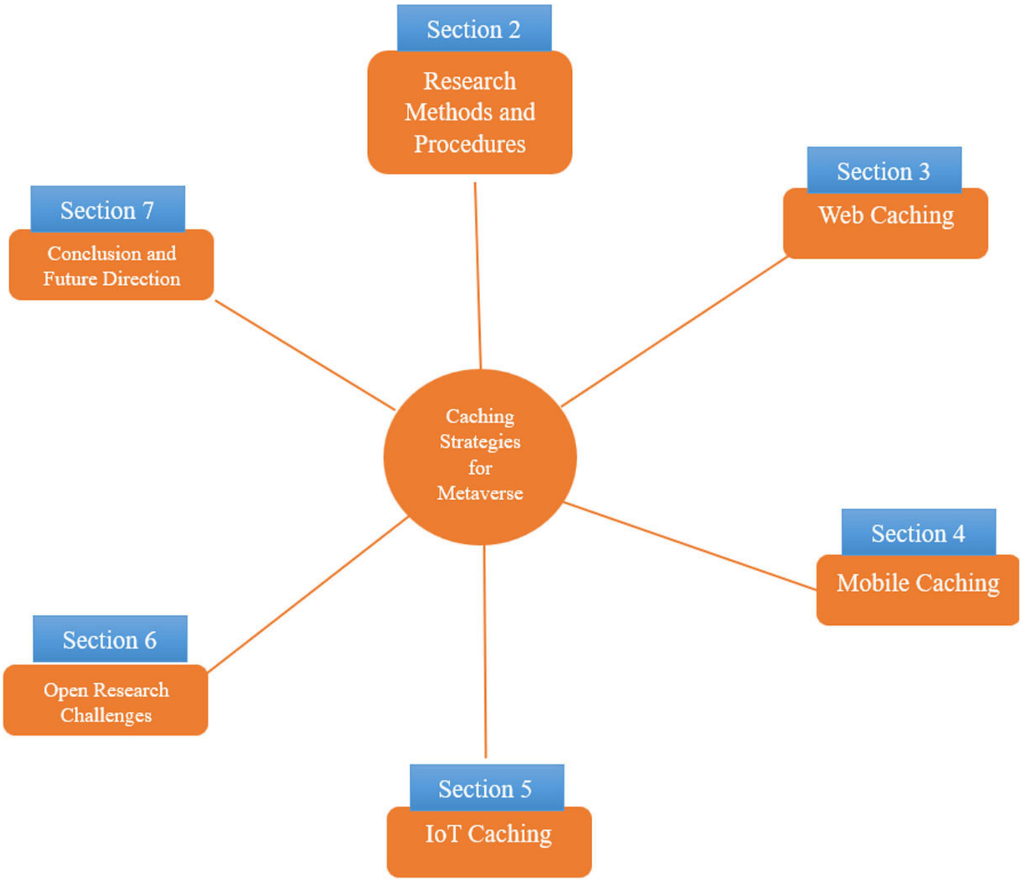

Fig. 1. Organization of this paper

2 RESEARCH METHODS AND PROCEDURES

In this section, the methodology used to conduct this study is explored. It includes the search options, selected databases, criteria, and chosen articles. For this study, standard peer-reviewed databases such as Springer, Science Direct, and IEEE Xplore were utilized.

To begin, we have constructed our query based on popular terms relevant to our topic. The query used functions similarly to a combination of targeted keywords. This question has been formulated to compile surveys addressing the topic of privacy preservation across different domains. Here is the query:

("Metaverse" OR "Mobile caching") AND ("IOT caching" OR "3 WEB CACHING") AND ("WEB3" OR "Caching strategies").

In order to identify gaps and progress from the endpoints, all the collected references have been thoroughly examined and debated in this research. Our search was conducted in accordance with the methodological requirements outlined previously, as depicted in Figure 2. We have compiled 65 journal publications, encompassing papers from various journals and periodicals.

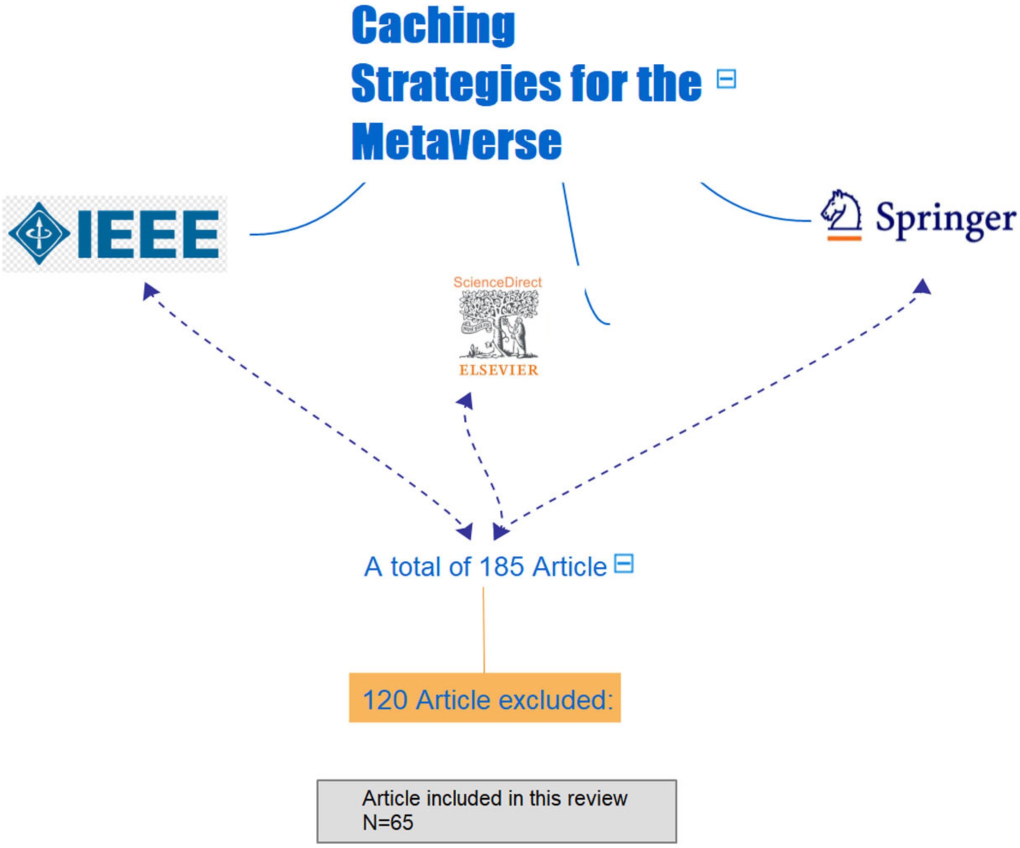

Fig. 2. Research methodology flowchart

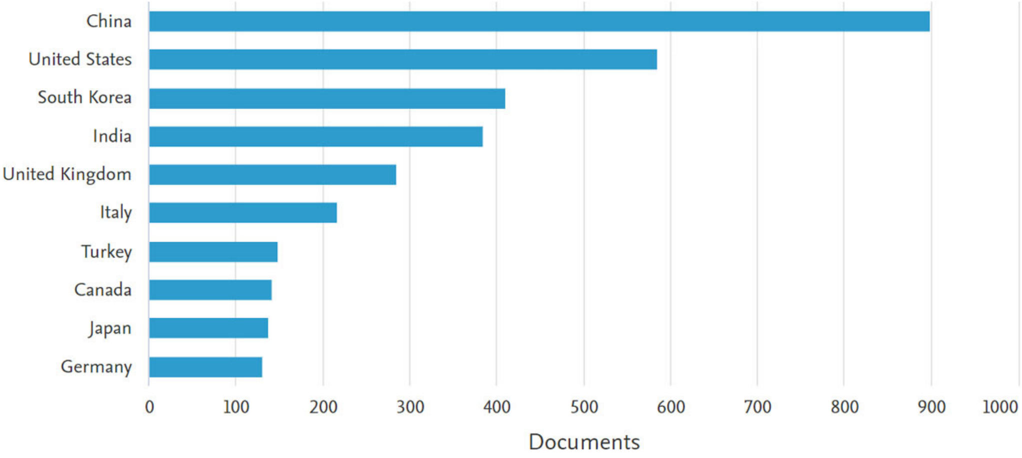

Fig. 3. Publications by country (2015 to 2022)

Shown in Figure 3 are national papers related to caching strategies for the metaverse that were issued between 2015 and 2024. Due to its ongoing concerns about implementing caching strategies for the metaverse, China has produced more papers than any other country in this field. The US published 584 papers, while South Korea published 406. The United Kingdom, Italy, and India each made significant contributions with 200 publications each.

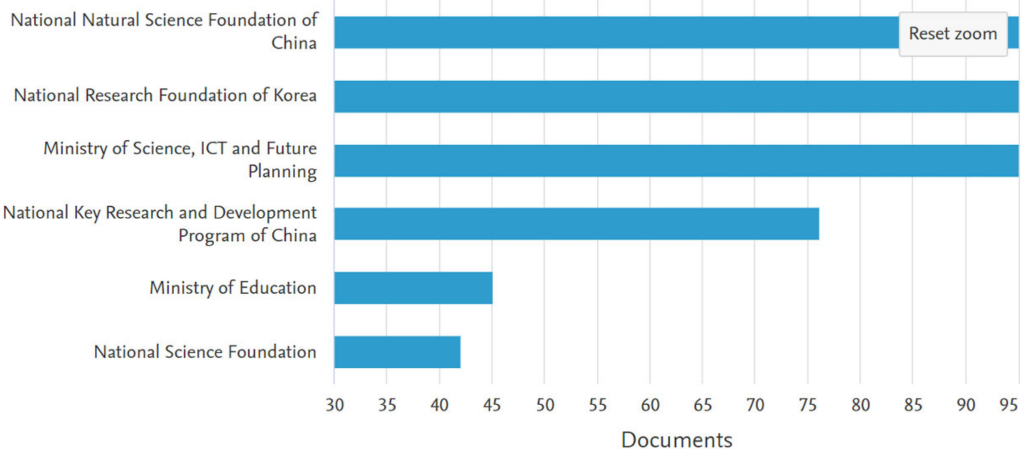

Fig. 4. Documents by top five funding sponsors

Documents from the five largest funders are shown in Figure 4. China is represented by the majority of the top five sponsors. The National Natural Science Foundation of China led with 275 papers, followed by Korea's National Research Foundation with 99 documents. Among the top five sponsors, the European Commission Framework Program had the fewest papers financed, with 41.

3 WEB CACHING

Web caching is a critical component of modern web architecture, playing a pivotal role in enhancing the user experience and optimizing network resources. It involves the temporary storage of web content, such as HTML pages, images, and multimedia files, at strategic points in the network.

When a user requests a web resource, the caching system checks to see if there is a copy of that resource in the cache. Once found, resources are delivered to the user faster, reducing latency and easing the load on the original server.

By reducing server load and minimizing data transfer over the network, web caching helps improve website performance and availability [21].

Web caching is one of the most effective ways to improve the speed of a web-based application. Popular online content that is expected to be accessed later will remain available for the user, either on a client computer or proxy server. Web caching enhances the process of eliminating web service bottlenecks, increasing internet traffic, and improving the scalability of the web system. Web caching offers the following advantages for users, network administrators, and content developers [21]:

- The perceived latency of the user's device is decreased through web caching.
- By caching web pages, network bandwidth usage is decreased.
- Web caching helps reduce the load on origin servers.
- Stale data and caching capacity issues.

The caching system's heart rate (HR) depends on the cache's size and pattern of use [22]. According to the researchers in [23], caching reduced the latency of collections of unmodified data items by half. By monitoring the HR, the appropriate cache size can be determined. The maximum cache size is reached as the cache size is steadily increased, and this happens just as the HR starts to rise very slowly. It all comes down to cost when it comes to cache capacity. If expanding the cache fails to generate the highest potential hit rate, it could be terminated.

The time-to-live (TTL), or client polling, is used to store data in the cache so that it can be retrieved as soon as the source server publishes a new update [9]. The TTL of data provided to the cache is determined by the origin server. When the TTL expires, the caching method re-requests data using information from the origin server. Through invalidation, data in a cache can be kept current with the latest updates on the origin server. In terms of polling, the client needs to regularly check the origin server for signs of any updated data.

Multilevel caching, weight-based caching, and data-mining-based caching are popular techniques increasingly employed in web applications. These methods serve to allocate tasks efficiently, improve overall performance, and alleviate server load. Multilevel caching, for instance, employs a hierarchical structure of caches to store frequently accessed data closer to the user, thus minimizing server requests. Weight-based caching and data-mining-based caching are also prominent strategies for optimizing system performance and the user experience. According to the popularity or relevance of the files, different weights are assigned, and then the files are cached using weight-based caching. Data mining-based caching involves examining user behavior to forecast upcoming requests and pre-cache those resources. Examples of data mining in action include adaptive cache allocation (ALC) and ALC prefetching, which use methods of data mining to discover correlations and patterns in data access. Figure 5 encapsulates the core concept of web caching, emphasizing its role in optimizing web content delivery and enhancing the user experience while also minimizing the load on the origin server.

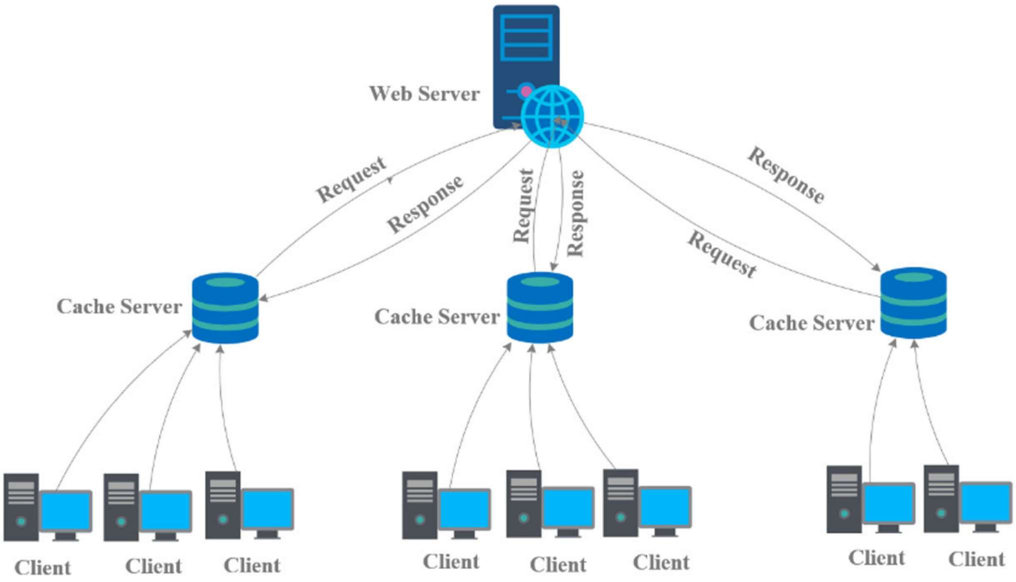

Fig. 5. Illustrates the overall design of web caching [24]

When a user accesses a website, the network is utilized to send a request to visit a specific web page. Subsequently, the network analyzes the request. In that instance, the network cache or the web cache sends another web request to the original web server. The original web server replies to the request by sending the necessary content to the cache. The content is then delivered to the client from the network cache, and it also stores the data locally.

The greedy dual-size least cost (GDS-LC) cache is designed with high-and low-priority divisions, considering both cost and latency. The study simulates three datasets using Amazon's basic storage capabilities, revealing that GDS-LC can achieve an average latency reduction of 21%.

Y. Im et al. [22] advocate a caching framework named C3C. This approach divides intersections, posting lists, and results into distinct caches. The result cache, which contains query results, has a backup cache for posting-list results in case the result cache lacks copies of the cached results. The caching intersection segment query results in slices for the posting-list cache. Using AOL query data as a dummy dataset, the study reveals that C3C boosted the hit rate (HR) by 7%.

J. Mertz et al. [23] introduced the weighting size and cost replacement policy (WSCRP), a caching strategy that incorporates weighted computations considering cost, frequency, and time. The policy selects objects for replacement based on a weighted value, accounting for the size, cost, frequency, and access duration of each object in the cache. Initially, objects with the lowest weighted values are replaced. After determining the weighted results, the final eviction list is obtained through sorting. Compared to other standard cache replacement policies, this strategy is suggested to decrease storage costs and increase the cache hit rate.

Researchers [25] explored how programmers approach application-level caching by studying ten online applications' design, implementation, and maintenance. The study delved into the source code of each application to identify employed caching techniques, such as in-memory caching, disk caching, and database caching. The findings revealed that programmers often utilize caching to enhance application performance by reducing database queries and server load. However, the study highlighted that the efficiency of caching is influenced by the employed mechanism and specific application needs. Cache invalidation and cache capacity management were identified as additional challenges, leading to recommendations for improving application-level caching. In conclusion, the research emphasized the practical application of application-level caching and stressed the importance of thoughtful design and implementation for optimal web application performance.

A caching method known as stimulable neural network (SNN) cache was presented for each machine learning-based sequence request [26]. Data receiving, data pre-processing, correlation filtering, and impulse computing were the four stages that made up the SNN caching method. The research was modeled using the Icarus Simulator (UCL Department of EEE), and SNN-cache was implemented to reduce server load. The fuzzy C-means algorithm, which has the following parameters: frequency, recurrence, and reference rate (FPRA), is used in the research conducted by S. Manikandan and M. Chinnadurai [27]. In the aforementioned research, it was discovered that clusters were present in just 10% of cache frames. If there are no clusters with the same member value, a process is performed to construct new clusters. Based on a C#-based simulator, the HR for this study was 50.61%.

Researchers in [28] proposed a caching framework known as C3C. This caching method stores intersections, posting lists, and results in separate caches. The result cache, a type of cache, contains the query results. In the scenario where the result cache does not contain any copies of the cached results, there is a backup cache for posting-list results. The caching intersection divided the query results into slices for the posting-list cache. In this study, AOL query data serves as a dummy dataset. The statistics show that C3C increased HR by 7%. The function-based semantic-aware caching approach (FSA) was suggested by R. Dong et al. [29]. The FSA assigned a ranking to cache pages based on the frequency with which pages were accessed. The navigation duration is calculated based on the proximity of the object cache to the pivot data. Previously, the FSA used well-known websites to select pivot data based on criteria of recentness, freshness, and frequency of access. There are no longer any objects in the cache that are in proximity to one another. In this research, data from the FIFA World Cup 1998 is analyzed. The results show that the FSA achieved an HR of 94% and a BHR of 75%.

Table 1 presents a summary of studies on web caching. When designing a caching system, it is crucial to carefully assess how the cache's size and location can impact its cost-effectiveness [30].

Table 1. Summary of studies on web caching

Authors	Year	Specific Issue	Algorithm	Findings	Limitations
Jhonny Mertz and Ingrid Nunes [26]	2020	Effort expensive and error prone, application caching.	Web applications	To get insight into how application-level caching is implemented by software developers.	Error-prone task. Time consuming.
Youngbin Im, Prasanth Prahladan [25]	2018	Common caching systems get a large number of requests for data.	Neural Network-means	Greatly lessens the burden on content servers.	Need to investigate latency ratio.
Davood, Ali Ebrahimnejad [27]	2020	Systems' performance degrades because the processors' speed is faster than the cache memory.	FCM	Improved overall human resources.	The latency ratio must be examined.
Thanh Trinh, Dingming Wu [22]	2019	Repeated outings There is a lot of wasted cache space.	3-level cache	By using the suggested approach, the number of duplicate hits is minimized compared to the current methods.	If the cache level fails, you'll need a backup plan.
Xuan Tung, Ngoc Dung [28]	2019	As Internet use grows, so does the amount of web traffic.	FSA	Outcome in terms of the number of bytes that were actually hit.	Need to improving BHR.

4 MOBILE CACHING

Mobile caching architecture is a crucial component in modern mobile applications. It involves the strategic storage of data, such as web content, images, and even application-specific information, on the mobile device itself or within a nearby network entity. The architecture typically comprises three key elements: the client-side cache, a remote cache, and a caching control mechanism. The client-side cache is local storage on the mobile device where frequently used data is stored. The remote cache, often located in a content delivery network (CDN) or a cloud-based server, acts as secondary storage for less frequently used or larger data sets. The caching control mechanism governs the coordination and management of the caches, deciding what data to store, when to update it, and when to evict it based on factors like usage patterns, expiration policies, and resource availability. This architecture optimizes data access, reducing latency, conserving network resources, and enhancing the overall mobile user experience.

Through the use of portable computing units (MUs), which wirelessly link to the servers in this type of computing environment, users can access data while on the go. A study on query processing in mobile database systems (MDB) was prompted by traveler information systems, mall sales, and train stations [31]. The data request is submitted via laptops, PDAs, and other devices with limited local capabilities. Wireless networks are susceptible to vulnerabilities due to frequent disconnections, poor communications, and capacity issues.

A practical solution to these issues involves data caching, in which frequently used data copies are stored on user computers. Managing caches involves considering consistency and replacement rules. Caching requires invalidation to maintain a consistent dataset for the client and server, and the cache replacement policy dictates which data is deleted when space is exhausted. Traditional distributed systems generate excessive network traffic and resource consumption in mobile computing.

Figure 6 illustrates mobile database cache management, emphasizing client cache analysis and categorizing data storage logically and physically. The edge caching network's architecture, serving as an intermediary between users and the Internet, promotes efficient communication via base stations. This network includes key components such as data center servers, the core network layer, mobile database cache management, and distributed edge caching mechanisms, significantly enhancing content delivery and the user experience. The system's core components—cache, management guidelines, and caching strategies—are emphasized in this design, comprising three primary layers: user, cache, and cloud.

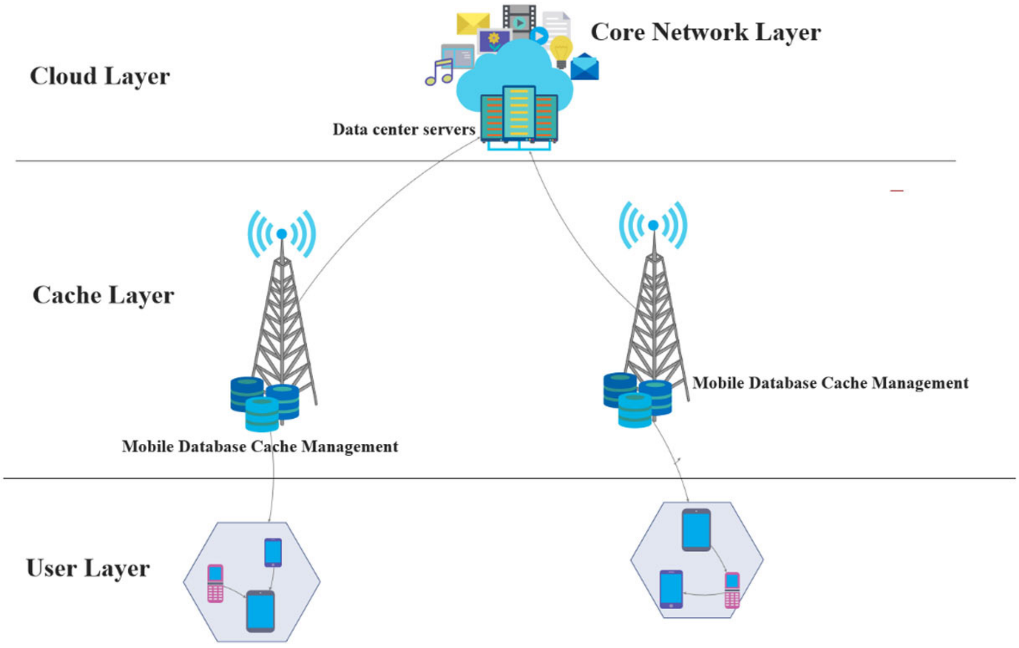

Fig. 6. The overall design of mobile edge caching networks [32]

The mobile device is represented by the user layer, which has a network connection to the cache layer. Edge servers, which store content cached closer to the mobile device, serve as the cache layer. These servers may be deployed at central stations or access points, for example, at different levels. The external cloud servers that provide additional processing and storage resources are represented by the cloud layer.

A CDN oversees caching regulations and methods, facilitating communication between the mobile device and cache servers. The CDN selects the best server to retrieve requested content based on variables like server location, popular content, and network circumstances. The database caching issues taxonomy is a classification system that effectively identifies and categorizes various challenges that can arise when implementing caching in a database. It includes categories such as cache invalidation, consistency maintenance, replacement policies, and cache coordination. Cache invalidation involves updating or removing cached data when it becomes obsolete.

Maintaining consistency between cached data and data stored in the database is known as consistency maintenance. When determining whether data should be replaced in the cache when there is not sufficient space, replacement policies are used. The process of ensuring that various caches in a distributed system remain synchronized and consistent with one another is known as cache coordination. When developing and implementing database caching solutions, the taxonomy can be used as a guide to identify potential problems and resolve them.

The physical data storage model stores cache contents (tuples or pages) as copies of server-side data items. In contrast, the logical data stores retain any query responses in the client's cache. Unlike the physical model, queries rely on the server to fetch data. This approach demands more processing power and ensures that only essential data is transmitted over the wireless connection.

The study [32] suggests a lightweight information management strategy that reduces memory requirements. The researchers designed and deployed SQLiteKV on a Google Nexus 6P smartphone. Throughout a single experiment, SQLiteKV outperformed SQLite by up to six times across various workloads. On average, heavy workloads resulted in significant performance gains, ranging from 12.7% for heavy workloads to 28.9% for read-most, 14.7% for heavy workloads, and 43% for read-latest. The read-latest workload, with a 256-byte request size, showed a performance improvement of 57% over the baseline when utilizing a coordination cache.

The researchers [33] investigated the interrelationships between new common-information measures for caching and existing measures. They specifically explored the connections between their suggested approaches and the common-information measures created by Wyner, Gács, and Körner.

Based on their findings, caching in multi-user situations could be enhanced by implementing the suggested approaches, resulting in higher hit rates and improved network performance. Moreover, the study demonstrated that the proposed changes effectively reduced network congestion, a critical consideration for caching systems. However, the lack of research to validate the effectiveness of these approaches in real-world scenarios is a notable limitation of their work. Furthermore, the suggested procedures may not be universally applicable to all types of caching systems and may require customization for specific applications.

In [34], the mentioned technique refers to a delivery strategy that employs coded multicasting and interference alignment to generate virtual receivers for each of the L transmitters. Each virtual receiver's share of each file is stored separately using this technique. This maintains all cache sizes within a multiplicative gap of NDT's optimum, and in certain regions, it is optimal.

The approach's results demonstrate that data caching may be performed more effectively by utilizing coded multicasting and interference alignment. This approach is beneficial in multi-user scenarios where multiple users require a single data item and the cache sizes are nearly optimal.

This method's requirement for interference alignment, which might be difficult to execute in some network settings, is one of its drawbacks. Moreover, the method relies on the assumption that each user necessitates the same data item, which might not always hold true.

Researchers in [35] describe schemes that establish limits on the amount of transmission power required to operate a specific cache capacity. The coded placement method performs better for small cache sizes and, in some cases, even exceeds the encoded placement lower bound limit. Placement of the cache without encryption requires less transmission power. By making use of the correlations between its contents, a cache-aided Gaussian BC may be capable of saving a significant amount of energy. Table 2 displays a summary of studies on mobile database caching.

Table 2. Summary of mobile database caching

Authors	Year	Specific Issue	Method	Findings	Limitations
Zhaoyan S., Yuanjing S. [32]	2019	IO interactions with the underlying file system that are not synchronized.	Sqlitekv	This study presented SQLiteKV improves performance by addressing the limitations of SQLite in data organization and coordination with the underlying storage system.	Needs Data Efficiency
Roy T., Shirin S. [16]	2018	Caching issue for a single user with associated sources.	F-separable distortion functions	You may alter the data that is stored in the cache to trade distortions across sources nontrivially.	**1.** Need data delivery rate **2.** Problem lost data **3.** Needs data quality
Fan X., Meixia T. [36]	2020	Peak-hour traffic congestion.	Normalized delivery time (ndt)	To get a lower ndt by completely using the transmitter's cache.	Data encryption
Qianqian Y., Parisa H. [35]	2020	Peak traffic hours are the worst for delays and congestion.	Superposition coding	It is expected to show that the offered coding schemes greatly improve bc energy efficiency over correlation-ignorant schemes.	**1.** There is a gap between the transmitting power as well as the lower limits. **2.** Sending less data than the user required.

5 IoT CACHING

Internet of Things caching, in the context of the IoT, plays a crucial role in optimizing data management and communication efficiency. It involves the temporary storage of frequently accessed IoT data at strategic points within the network. This cached data can significantly reduce the latency associated with data retrieval and processing, leading to improved real-time IoT applications and services. By intelligently caching data closer to where it's needed, IoT caching helps alleviate the burden on network resources and enhances the overall responsiveness and scalability of IoT systems.

In 2022, the IoT connected 14.3 billion devices, indicating a significant amount of data processed every minute. To meet these demands, IoT will need considerable time to transmit data to the cloud, perform services on it, and then return it. Edge computing utilizes a distributed network instead of relying on a single data center for cloud computing to reduce the roundtrip time to the cloud, offer real-time responses, and enable local control. Smartphones, tablets, and home security systems are examples of end-user applications and devices that generate and consume substantial amounts of data. According to a research study by IDC [37], 45% of the data generated by IoT devices will be stored, analyzed, and processed on the network by 2022.

Optimized for real-time responses catering to consumer demands for low-latency applications such as swift music downloads and seamless movie streaming, edge computing emerges as a critical solution. This is particularly vital in scenarios where immediate responsiveness is imperative, such as in autonomous vehicles (AV), where even a millisecond delay can pose serious safety concerns. AVs adeptly adapt to prevent collisions, emphasizing the need for instantaneous processing. Additionally, in emergencies like fires, the rapid transmission of signals from smoke detectors becomes crucial within seconds. Furthermore, the ability to anticipate environmental hazards and take timely precautions underscores the significance of edge computing in predicting and addressing potential issues. In all these situations, connecting to the cloud might introduce catastrophic delays, highlighting the indispensable role of maintaining low latency [38].

As illustrated by the green line, the process of retrieving uncached data from the edge node involves several steps. Initially, a request message is received (the first step of the green line) and then forwarded to the data producer (the second step of the green line) [39]. Subsequently, the data producer transmits the requested data to the data consumer (the third and fourth steps of the green line) through the edge node. In the edge caching-based IoT scenario, the edge node enables the caching of data items.

Internet of Things edge caching is an approach that reduces latency and network traffic by storing frequently accessed data near the devices that require it at the edge of the network. The most significant components of an IoT edge caching system typically include IoT devices, edge nodes, and a caching controller.

These elements are depicted in a simplified layout in the illustration designated “Edge caching-based IoT system.” The edge nodes are responsible for caching the data and serving it to the requesting devices. The IoT devices, represented as sensors, generate data that is transmitted via the network to the edge nodes. Decisions about which data should be cached, where it should be stored, and for how long are all made by the caching controller, which also manages the caching policies [40]. The illustration also demonstrates how the edge nodes can connect to the cloud, providing access to additional computing power as needed. By reducing network congestion and latency and enabling faster data access, this system architecture enhances the performance of IoT applications.

Several studies [41] have shown that IoT data, even if it expires after a predetermined amount of time, is extremely advantageous to network performance. Various distributed caching techniques have been utilized to reduce the latency and energy consumption of data retrieval in wireless sensor networks [28]. The lifespan of the content becomes crucial for each sensor node when deciding when to cache it; a longer lifespan indicates an increased probability of caching.

The caching model proposed in [42] introduces an approach that considers the relationship between data longevity and multi-hop communications when selecting a caching strategy. When data is obtained from the producer, which is larger in the same scenario, communication and quality costs are reduced and traded off for each prospective cache in a cost function. A consumer application will value the cost of connection more and the quality of the data it could acquire from an out-of-range network less, the higher the communication coefficient. IoT application developers and network operators need to compromise on a service-level agreement to set specific coefficient values [43]. The aforementioned approaches rely on local content and network characteristics to make decisions, which is not compatible with our suggestion. While the authors in [44] focus on a single edge node, they also discuss the base station or gateway as a single point of entry to the network.

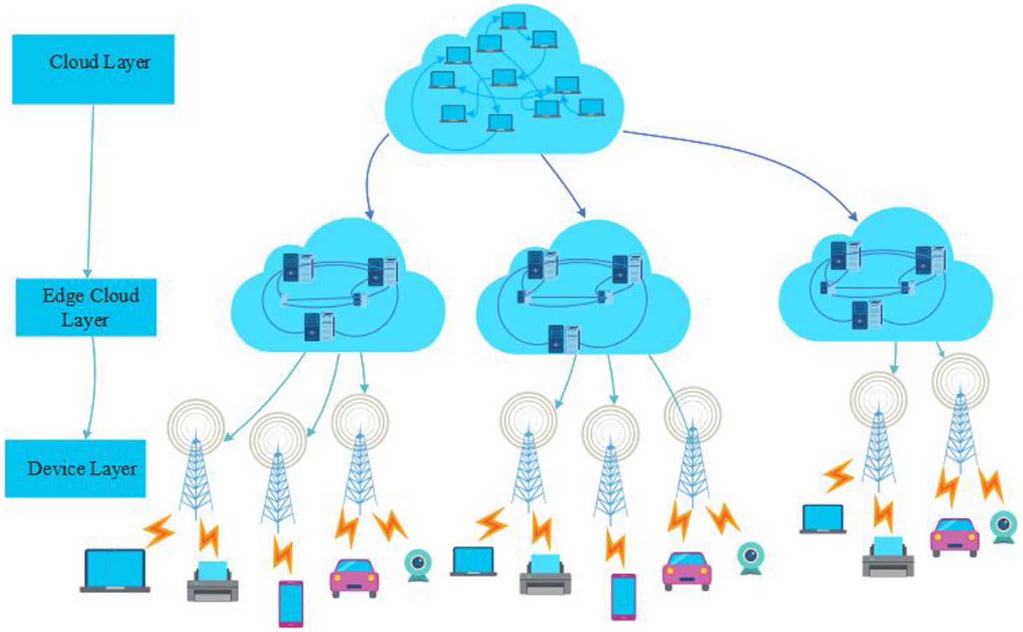

Fig. 7. Distributed IoT caching architecture [35]

In this prioritization, the retrieval of information from a single edge node or primary source over communication costs is crucial. Deep reinforcement learning is being utilized to forecast future environmental conditions and choose information for caching due to the uncertainty surrounding the potential popularity of IoT data. In [45], the suggestion is to cache data on a single edge node, which functions as an IoT gateway for multiple providers.

When deciding whether to cache data, the popularity of a piece of content is taken into consideration. Following our recommended approach, caches are network nodes with more lenient energy restrictions but less storage capacity compared to cloud storage. The idea of gauging progress in the digital era by counting the years since a cached item's creation has been utilized to illustrate the temporary nature of IoT content [46]. The age of cached content is quantified by the age of information (AoI); the goal is for each user to access only the most recent version of the content. The AoI literature has introduced decision-making techniques for optimizing cache updates in situations with restricted bandwidth or sporadic connections [47].

In order to decrease AoI, researchers [48] have examined the most effective techniques for scheduling packets on IoT devices with limited resources. On the other hand, the focus of our research is on the edge caching of IoT contents generated consistently by IoT sources, such as those used for monitoring. Each application-specific, predefined lifetime for the cached data ensures that it is automatically flushed when it reaches the end of its useful life. As a result, each cache can only provide the most recent version of an object's content and does not store previous data. Figure 7 depicts a distributed IoT architecture, highlighting the integration of IoT devices to enhance data security, transparency, and automation. The key advantages of this architecture include data integrity, decentralization, and the ability to create trust and automation within IoT ecosystems.

In the study [49], it is demonstrated that the proposed approach outperforms in terms of latency and cache hit probability in all simulated scenarios. The metrics were obtained by generating confidence intervals of 99% and averaging the results from 100 runs.

According to the authors, R. D. Yates et al. [50], the proposed approach suggests that the broker can cache frequently accessed resources to optimize server energy consumption while minimizing the average publishing delay for individual clients. The content of each IoT resource is generated by a Poisson distribution, with a mean of 500 kB for each server.

Researchers [51] proposed the rapid content access method and IoT application-specific caching architecture in the paper, which are based on unique ICN clustering and caching approaches. The proposed caching approach may be used to improve overall network efficiency. As CCN nodes, all nodes are now capable of generating interest packets, serving as routers, and distributing content. The increasing demand for efficient data retrieval in IoT networks has led to the development of various caching techniques. Reduced latency, increased data availability, and best use of network resources are the goals of these methods. Table 3 gives an outline of various methods.

Table 3. Summary of IoT caching techniques

Authors	Year	Specific Issue	Method	Findings	Limitations
Giuseppe R., Marica A. [46]	2021	Cut down on the amount of time it takes to get data from the core network.	Integer Linear Programming (ILP)	The assessment shows that the proposal is preferable than a baseline approach, regardless of the content's freshness, despite the fact that the evaluation was undertaken.	**1.** Data transferred through SDN is not in the cloud. **2.** The data transfer time is not enough.
Xiang S. and Nirwan A. [43]	2018	The energy consumption of servers.	Resource caching that is energy-aware and latency-guaranteed (ease)	Guaranteeing the minimum average delay.	It needs to store data.
Kamrul Hasan and Seong-Ho Jeong [46]	2021	Very low response time.	Information-Centric Networking (ICN)	Content transfer time and efficient content caching.	The number of nodes used must be counted.
Wentao Yang and Zhibin Liu [43]	2024	Data Security and Privacy.	Vehicular Edge Computing (VEC)	The effectiveness of the AFLR scheme in improving cache hit rates and reducing content transmission delay in VEC.	Not be able to participate in timely model updates due to their off-grid behavior.

6 OPEN RESEARCH CHALLENGES

Exploring effective caching strategies for the metaverse presents a set of open research challenges. This section delves into addressing these intricate issues to optimize caching mechanisms in the evolving landscape of the metaverse.

6.1 Web caching

The metaverse introduces new challenges to data mining and web caching strategies. In this context, the integration of data mining techniques with web prefetching and caching presents both opportunities and limitations. Data mining, which involves uncovering patterns and trends in large datasets, has benefited from advances in machine learning, particularly in classification and clustering tasks. Support vector machines (SVMs) and artificial immune systems (AISs) are commonly used data mining techniques that have been applied to enhance web proxy caching and prefetching in the metaverse.

Web developers can employ web caching and prefetching as separate strategies to enhance web application speed. Prefetching can replace cached items and also enable the utilization of cached data, potentially creating synergies between the two techniques.

Researchers have proposed a cache ability design as a foundation for integrating web prefetching and caching. The design suggests caching frequently-accessed objects first, followed by prefetching objects likely to be requested in the future [52].

However, these techniques also come with limitations. Web prefetching may lead to unnecessary network traffic and might not consistently improve web application performance. Furthermore, the effectiveness of web prefetching and caching relies on the specific characteristics of the application and user behavior, making it challenging to apply these techniques universally across different metaverse contexts.

As the metaverse continues to evolve, addressing these challenges will be crucial in designing efficient and adaptive data mining, caching, and prefetching strategies tailored to the unique requirements of this new paradigm. Research efforts in this area will play a vital role in optimizing user experiences and performance in Metaverse applications.

6.2 Mobile caching

In the context of the metaverse, caching plays a crucial role in enhancing mobile data access speed. A study by the authors [53] utilized an object-oriented database to develop a caching framework with the specific aim of improving data access speed for mobile clients. The framework leverages the local database management system of the mobile device to implement caching [54].

The study observed that the caching strategy was particularly effective in reducing network traffic when the request renewal process occurred in bursts, leading to significant improvements over static caching. Although the primary focus was on wireless networks, the findings are applicable to any distributed caching scenario [55].

Furthermore, the study explored the potential of repair-efficient coding techniques, such as regenerating codes, to further reduce network traffic. By implementing the proposed caching framework, mobile users can benefit from faster data access and reduced network load, ultimately enhancing the overall user experience in the metaverse [56].

This research highlights the significance of efficient caching mechanisms in the metaverse, especially in mobile environments where network resources are often limited. By optimizing caching strategies, developers can enhance performance and responsiveness in metaverse applications, enabling users to interact seamlessly with the virtual environment on their mobile devices.

6.3 IoT caching

Caching data from IoT devices in the network is to be cost-effective. Caching at content routers can be a good alternative to reducing source retrievals when billions of IoT devices are connected to the internet. However, caching IoT data pieces is more complex than caching huge data files or multimedia data. The lifespan of IoT data depends on the application that requests the content or the end user, such as a web browser [57]. Distributing copies of frequently requested content over several edge nodes closer to end users can be performed to balance the competing demands of content variety and maximize cache effectiveness [58]. To achieve these goals, the intended caching approach can be improved upon in further research. Additionally, given that edge infrastructures are evolving towards distributed in-network computing systems, the controller's capacity to coordinate the pairing of caching and processing services might need to be enhanced [59].

Ensuring metaverse caching infrastructure prioritizes user data privacy, adapts caching mechanisms dynamically to diverse content formats, and addresses latency challenges for real-time synchronization across distributed caches can enhance the overall user experience.

7 CONCLUSION AND FUTURE DIRECTION

Enhancing data and transaction management in online databases, mobile environments, and IoT databases has received a tremendous amount of attention in recent years [58]. Data and transaction management are far more challenging to handle than in conventional databases because mobile databases need to be highly adaptive and comply with various resource constraints.

The website administrator needs to deal with a lot of data due to the growth in web-based applications. The rise in factors such as response time, bandwidth, and storage capacity increases the likelihood of encountering more issues. Caching can help decrease latency on both the server and client sides. This article delves into the topic of invalidating and replacing mobile database caches. We have provided a taxonomy to address this matter.

The most important aspects of cache management for physical storage have been discussed, such as query invalidation due to temporal and location-dependent changes and cache replacement based on the validity of data items.

Blockchain technology has been utilized by professionals to establish a reliable, decentralized transportation network. Researchers [60] have developed a secure peer-to-peer (P2P) vehicle data sharing system using vehicular blockchain.

The combination of SDN and blockchain technologies allows for secure, low-latency access to vast amounts of data. Achieving high availability, real-time data transmission, scalability, security, and low latency is possible through the implementation of a distinctive blockchain-based distributed edge cloud architecture to manage the growing volume of data produced by smart devices. This approach focuses specifically on trading computational resources for edge-cloud-assisted IoT [61], with an emphasis on a crowd-intelligence ecosystem [50]. The use of blockchain systems was enhanced [62].

There are a limited number of studies that discuss a distributed edge cloud architecture based on blockchain that may utilize content caches to reduce network delays, recurring transmissions, and backend bandwidth consumption.

By 2025, there will likely be 25 billion IoT devices in use across our society [63]. The cloud receives an immense quantity of data from these distributed devices to deliver services. This raises the issue of expanding, securing, and managing resources while relying on external parties to protect private data.

A distributed blockchain caching architecture has been proposed as an approach to these problems. Applications can now be distributed via blockchain technology instead of relying on a third party [64]. The challenge of IoT devices struggling to meet the increasing demand for IoT data could be addressed with edge computing technologies. By utilizing resources closer to the edge of the IoT network, end users can access cloud services such as storage, computing, and networking more quickly.

Nevertheless, specific applications necessitate local storage for rapid transfers and swift response times [65]. The substantial expenses in terms of bandwidth, energy, and time associated with redundant data transit have spurred interest in deploying content caching at the network's edge. The rapid expansion of a content distribution network (CDN) and an information-centric network (ICN) has paved the way for the integration of content caching into blockchain-enabled IoT. Placing a cache at the user's network edge can reduce backlink bandwidth and network latency. Various technological advancements are currently showcasing this emerging trend. A well-devised selection strategy holds the potential for enhanced end-user satisfaction and cost-effectiveness.

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