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Cloudlet Computing: Recent Advances, Taxonomy, and Challenges

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ABSTRACT A cloudlet is an emerging computing paradigm that is designed to meet the requirements and expectations of the Internet of things (IoT) and tackle the conventional limitations of a cloud (e.g., high latency). The idea is to bring computing resources (i.e., storage and processing) to the edge of a network. This article presents a taxonomy of cloudlet applications, outlines cloudlet utilities, and describes recent advances, challenges, and future research directions. Based on the literature, a unique taxonomy of cloudlet applications is designed. Moreover, a cloudlet computation offloading application for augmenting resource-constrained IoT devices, handling compute-intensive tasks, and minimizing the energy consumption of related devices is explored. This study also highlights the viability of cloudlets to support smart systems and applications, such as augmented reality, virtual reality, and applications that require high-quality service. Finally, the role of cloudlets in emergency situations, hostile conditions, and in the technological integration of future applications and services is elaborated in detail.

INDEX TERMS Cloud computing, edge computing, cloudlets, Internet of Things, computation offloading, smart city, smart health.

I. INTRODUCTION

Cloud computing offers resource-rich, flexible, scalable, and cost-effective solutions to users across the globe. In addition, cloud computing provides high processing power, expensive hardware, multivendor platforms, and millions of applications over the Internet. The influx of users saving their data and resources online while on the move increases daily. Since 2010, users interests have shifted from desktop and laptop computers to mobile phones for Internet surfing, social networking, e-mail accessing, online gaming, and other interactive applications. Statistics show an increase in users by up to 3.8 billion by 2021, 80% of whom will use smart phones for Internet surfing [1]. Clouds offer high processing power, considerable memory and storage, and a range of applications/services to meet users rising needs. Despite their numerous advantages, clouds are located far from users and connected through multiple hops, which incur high latency. Regions with low or no technological infrastructure, specifically, environments with disconnected, intermittent, and limited (DIL) connectivity, can compound problems or degrade cloud services to suboptimal levels. Despite high technological advancements, mobile devices are unable to match their desktop counterparts in terms of computational power. Moreover, mobile devices have low processing power, short battery life, and limited memory and suffer from heat dissipation issues and high latency in cloud environments [2]. The performance of mobile devices degrades substantially when they are operated in hostile environments for applications such as image recognition, situation awareness, and language translation or decision-making systems, which require heavy computational power and long battery life [3]. To overcome these limitations, researchers developed a solution called edge computing. Cloudlets [4], [5] are a type of edge computing that aims to bring cloud applications, capabilities, and services to the network edge and closer to users, specifically, a single hop away [6]. Figure 1 depicts a simplified cloudlet architecture.

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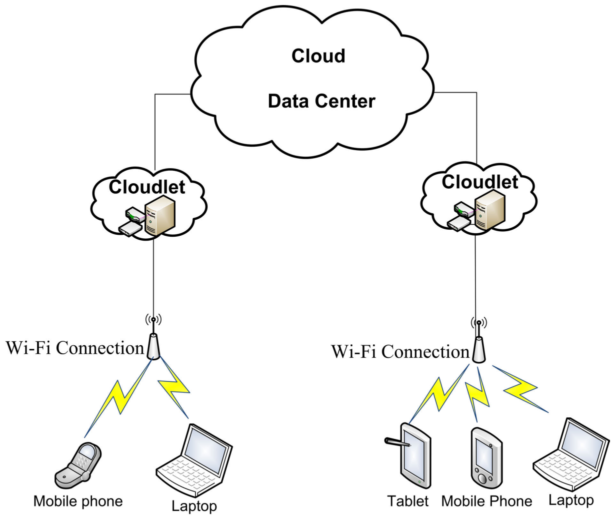

FIGURE 1. Simplified cloudlet architecture.

Cloudlets can be used in environments where superior situation awareness, decision making, and reliable connectivity (RC) are required. Cloudlets can be integrated with sensors, image processing, pattern recognition, and video analytics to improve performance. Such technologies are compute-intensive and have stringent quality of service (QoS) requirements that can be achieved using cloudlets, which are located in users locality and can provide considerable processing capabilities and low communication latency. Cloudlets can continually provide services in the absence of an enterprise cloud and subsequently synchronize their activities with the cloud when it comes alive. In this manner, cloudlets can provide users with persistent connectivity.

Most existing studies focus on general cloudlet applications and deployment strategies for achieving monetary means and managing resources in computation offloading environments. The major contributions of this study are as follows:

1 Investigates and summarizes previous studies on cloudlets to provide a comprehensive review of the recent literature
2 Explores the requirements of real-time, near real-time, and interactive applications, such as augmented reality (AR), virtual reality (VR), and online games, that demand quick response, superior QoS and quality of experience (QoE), and context awareness; discusses the potential of cloudlets to achieve such requirements in the existing saturated Internet architecture
3 Presents an overview of the challenges of IoT-based smart systems, such as smart city, smart health, and so on, and cloudlet support to cope with challenges, along with the proposed methodologies based on cloudlets, as smart systems are reshaping the technological landscape of the world
4 Discusses how different computation offloading design strategies, such as application offloading, component offloading, and virtual machine (VM) image offloading, can affect compute-intensive applications; provides a rationale for when and what to offload, along with computation offloading complexities, such as cloudlet discovery, thread interdependency and migration, context gathering, remote execution calling, synchronization and scheduling overhead, and application partitioning, which should be considered when working with computation offloading
5 Discusses the potential of cloudlets to provide continuous service in hostile conditions, such as emergencies and military operations, and data-intensive applications that benefit from data-staging techniques in cloudlets and communication-intensive applications that fancy a network as a service (NaaS) technique that leverages cloudlets substantially in difficult conditions
6 Presents significant open research issues that require attention

The rest of this paper is structured as follows. Section II reviews similar studies and highlights how this work differs from others. Section III illustrates the cloudlet utilities, followed by Section IV, which describes the extensive taxonomy of cloudlet applications. Section V outlines the challenges and future directions of cloudlets, and Section VI presents a critical analysis of the cloudlet architecture, challenges, open issues, and existing solutions. Finally, Section VII concludes the paper and presents future works.

II. RECENT ADVANCES

Cloudlets are an emerging paradigm that was investigated extensively in various aspects. For example, the authors in [7] described cloudlet applications and usage challenges from the perspective of a thin and thick client. The existing study in [9] discussed the potential benefits of cloudlets in wireless local area networks (WLANs). The authors envisaged technical complexities while deploying cloudlets in LAN commercially and considering key factors, such as scalability, mobility, and deployment cost [14]. The authors work primarily focuses on the energy conservation of cloudlets and critically analyzes the role of different algorithms in minimizing energy consumption. In [15] the author presented a two-tier cloud in a cloudlet architecture using a fiber-wireless (FiWi) networks. Considering future 5G mobile networks moving toward cloudlet-based decentralization, the authors reviewed the suitability of mobile edge computing for emerging applications, such as AR, VR, cognitive assistance, and cloud robotics. Cloudlet computing in [16] presented a brief review of computation offloading methods to address the resource scarceness of mobile devices and highlighted current advancements in computation offloading in the industry, such as MAUI [17], Oddessa [18], CloneCloud [19], and COMET [20]. Table.1 summarizes relevant surveys on cloudlets published in the past five years. Most of the studies focus on specific cloudlet aspects. Table.1 clearly shows that the scope of our survey is more comprehensive than that of the contemporary studies.

TABLE 1. Focus of existing surveys.

References	Year of Publication	Cloudlets application in general	Energy efficiency	Computation offloading techniques in Cloudlets	Resource provision and allocation	cloudlet and other edge computing platforms such as fog, MEC, MCC comparison	Deployment, location, and discovery of Cloudlets	Role of Cloudlets in hostile conditions	Analysis of latency critical, Interactive, and context-aware applications	Smart systems challenges and Cloudlets support	Future direction
Z. pang et al. [21]	2020	✓	✓	x	x	✓	x	x	x	x	✓
Chamola, Vinay et al. [22]	2020	✓	✓	x	x	x	x	x	x	x	x
Ren. Ju et al. [23]	2019	✓	✓	x	x	x	✓	x	x	x	✓
Dimopoulos, Stratos et al, [24]	2019	✓	✓	x	x	✓	x	x	x	x	x
Elazhary, Hanan [25]	2019	✓	x	✓	x	✓	x	x	x	x	✓
kashif. bilal et al. [26]	2018	✓	x	x	x	✓	x	x	x	✓	x
Nayyer, M Ziad et al. [27]	2018	✓	✓	✓	✓	✓	x	x	x	x	✓
Gedeon, Julien, et al. [28]	2018	✓	✓	x	x	✓	x	x	x	x	x
usman shaukat et al. [9]	2016	✓	✓	x	x	✓	x	x	x	x	x
Jararweh, Yaser et al. [29]	2014	✓	✓	x	x	✓	x	x	x	x	x
This Survey		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Unlike Table 1, Table 2 summarizes studies that focus on a particular cloudlet aspect, such as latency reduction (LR), bandwidth saving (BS), service and Internet monitoring (S and IM), energy saving (ES), reliable connectivity (RC), and application streaming (AS).

III. CLOUDLET UTILITIES

Cloudlets offer numerous utilities, such as lowering communication latency and improving connectivity. Cloudlets use Wi-Fi connections and extend the battery life of mobile devices by offloading compute-intensive tasks to a cloudlet for processing. Cloudlets, combined with an enterprise cloud, such as Google, are beneficial, as they provide applications and services to users. Moreover, cloudlets do not need to reach an enterprise cloud to synchronize themselves with others. However, when reaching an enterprise cloud is necessary, cloudlets process most of the data and send less traffic toward the cloud, resulting in low data storage requirements, low bandwidth, and reduced communication latency, delays, and jitters [56]. Apart from these key advantages, cloudlets provide benefits essential in interactive gaming environments, user satisfaction, and users freedom to use them without fear of privacy and security issues. Figure 2 articulates the cloudlet utilities.

TABLE 2. Summary of cloudlet literature.

Article	LR	BS	S and IM	ES	RC	AS
[9]	✓	✓	✓	✓	✓	✓
[30]	✓	χ	χ	✓	✓	χ
[31]	✓	χ	χ	✓	✓	χ
[32]	✓	χ	✓	χ	✓	✓
[33]	✓	χ	✓	✓	χ	✓
[34]	✓	χ	✓	✓	χ	✓
[35]	✓	✓	✓	✓	✓	✓
[36]	χ	χ	χ	χ	χ	✓
[37]	χ	χ	✓	✓	χ	χ
[38]	χ	χ	✓	χ	✓	χ
[31]	✓	✓	✓	✓	✓	✓
[39]	✓	✓	✓	✓	✓	✓
[40]	✓	χ	χ	✓	χ	✓
[41]	✓	χ	χ	χ	✓	χ
[42]	χ	χ	χ	✓	χ	χ
[43]	χ	χ	✓	χ	χ	✓
[44]	✓	χ	χ	χ	χ	χ
[45]	χ	χ	χ	χ	χ	✓
[46]	χ	χ	✓	χ	✓	χ
[47]	✓	χ	χ	✓	χ	χ
[48]	✓	χ	χ	χ	χ	χ
[49]	χ	✓	χ	χ	✓	✓
[50]	χ	χ	χ	χ	χ	✓
[51]	χ	χ	χ	✓	χ	χ
[36]	χ	χ	χ	χ	✓	χ
[20]	χ	χ	χ	✓	χ	χ
[52]	χ	χ	χ	✓	χ	χ
[53]	χ	χ	χ	✓	χ	χ
[54]	χ	χ	χ	✓	✓	✓
[26]	χ	χ	χ	χ	χ	✓
[33]	χ	χ	χ	χ	χ	✓
[55]	χ	χ	χ	χ	χ	✓

A. RAPID RESPONSE

The emerging trends of network localization, distributed clouds, ubiquitous computing, and 5G technologies give life to computationally hungry, storage-intensive, and highly responsive applications. Such applications reside in a wide technological domain, including automated and intelligent driving, advanced maps with real-time data, and video streams to connected vehicles, with the list growing rapidly [35]. Most of the aforementioned applications require rapid response, which cloudlets can address with flexible placement strategies. Cloudlets enfold execution resources, such as storage and computation, close to sources that generate data, which effectively improves application response.

B. CLOUDLETS SUPPORTING NEW TECHNOLOGIES

Cloudlets are scalable and can meet future demands when a network, system, or organization grows. Moreover, cloudlets can easily accommodate new communication devices,

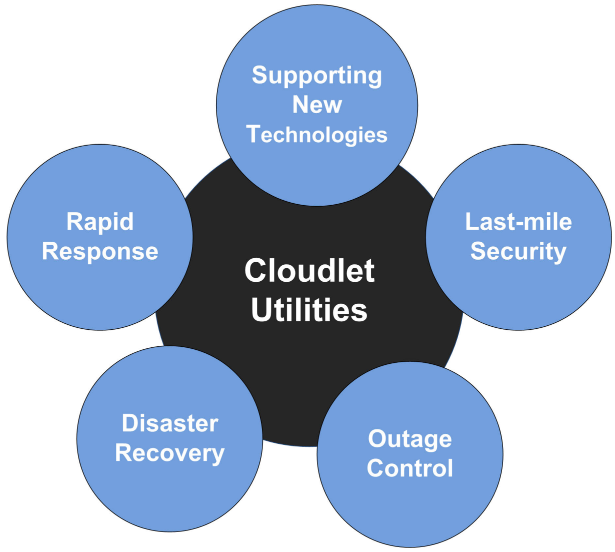

FIGURE 2. Cloudlet utilities.

services, and policies and do not require overlay networks compared with the existing Internet architecture, which is exceedingly saturated; thus, researchers often look for overlay networks for placing new products and services. Emerging cloud technologies include mobile edge computing, fog computing, and cloudlets bringing cloud services to the leading edge of a network. Cloudlets are merely one or a few hops away from users and can reduce incoming bandwidth requirements for the cloud by three to six orders of magnitude for certain applications [38], such as edge analytics, which processes or filters data at the edge of a network, and image processing, in which video camera feed preprocessing is desirable. Cloudlets process entire video feeds but transfer only pertinent events to the cloud. Similarly, in a facial recognition system, only the occurrence of a particular event is searched, and only the required events are transferred to the cloud. The cloudlet in this architecture filters unwanted traffic reaching the cloud and provides opportunities to block infectious and malicious contents from reaching the cloud by implementing first-level security near the users vicinity.

C. LAST-MILE SECURITY

A cloudlet is the first point of connection to users, where a security policy of their needs can be deployed before data are transferred to the cloud. This process can address security issues in enterprise clouds, in which users have no control over data movement, cannot implement the security policy of their choice, and have no idea who is securing and how. Through cloudlets, users can prevent certain types of data being sent to the cloud. For instance, important data, such as personal information, corrupt data, blurry videos, and sensors producing data in bulks, can be filtered and processed locally over cloudlets, which will forward only the required data to the enterprise cloud [57]. The Akamai Cloudlet [51] and Nokia MEC [58] are beneficiaries of first-line security through edge analytics.

D. CLOUDLET OUTAGE CONTROL

Cloud outage is a major concern for users. The most common operational failures include interruption of service to enterprises, frozen applications, and violating committed QoS to users. Moreover, outages can affect the public confidence in cloud technology. Gang and Zeng in [23], described cloudlet outages in cyber foraging, data access, and collaboration. Outages reflect a denial of service (DoS) in terms of application access failure, data access failure, and failure to work in collaboration with other users. Outages will also restrict closely positioned users from collaborating owing to an overlay conventional synchronization strategy. VM-based cloudlets can overcome users inability to access a cloud in critical situations. VM-based cloudlets can provide services to users in the absence of an enterprise cloud. However, if synchronization with a cloud is required, then cloudlets will synchronize their activities when cloud services become available.

E. DISASTER RECOVERY

Natural disasters can neither be predicted accurately nor prevented, such as the tsunami in the Indian ocean in 2004; flooding from hurricane Katrina in 2005; the earthquake in Pakistan in 2005 and in Haiti, and Chile in 2010; and so on. Such disasters can destroy technological infrastructure on a monumental scale. In a disastrous situation, a cloud is a single point of failure. If a cloud fails, then all the applications and services that rely on the cloud will likewise fail. Cloudlets bring the disaster recovery degree to the next level, that is, the application level [30]. When a cloud fails, critical processing may continue via cloudlets, but the least important compute-intensive tasks may be lost. Disaster prevention is nearly impossible, but the substantial damage caused by disasters can be mitigated with cloudlets. In situations such as military operations in hostile conditions, security personnel require continuous mobility and have no time to deploy a cloud. Cloudlets can be deployed instantly and easily in such environments and promise software and hardware heterogeneity, interoperability, security at the users vicinity, bandwidth efficiency, and latency reduction.

IV. TAXONOMY OF CLOUDLET APPLICATIONS

Users interest to execute compute-, data-, and communication-intensive tasks with mobile phones increases daily. However, such devices are resource constrained, and related applications are resource hungry and require low latency, high bandwidth, bundled services, and persistent connectivity. This section highlights the viability of cloudlets to support emerging technologies. The taxonomy in Figure 3 aims to highlight the efficiency of cloudlets in six broad areas, that is, LR, BS, communication and network S and IM, energy efficiency, RC, and video streaming. These fundamentals empower resource-poor devices, such as mobile phones and other handheld devices, to avoid rapid battery drain and accomplish compute-intensive tasks and bring clouds closer to users. Services that can be accessed via clouds are desirable. However, complications, such as intermittent connectivity and resource-constrained devices with limited battery life, memory, and processing power, can restrict users from the potential benefits of clouds and worsen situations in DIL environments [59].

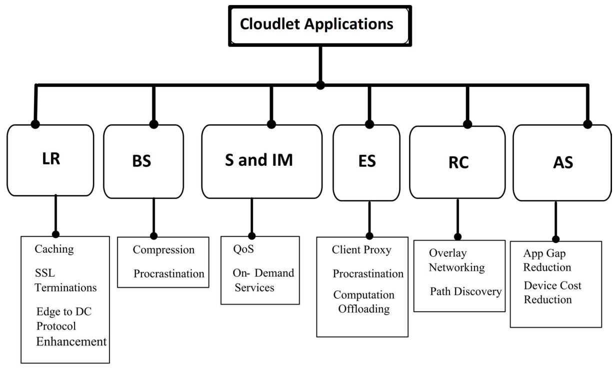

FIGURE 3. Taxonomy of cloudlet applications.

A. LR IN CLOUDLETS

Networks are intentionally designed to increase utilization and throughput. However, network latencies emerge as performance bottlenecks in the Internet environment of current and emerging applications. The usability of an application lies in its interactivity and responsiveness, which are largely dependent on latency [44].

Marrisa in [60] described latency as the measure of an applications responsiveness. LR can improve an applications effectiveness, efficiency, and interactivity. High latency can affect user experience and make applications sluggish and jerky. In addition, latency can increase costs. For instance, a joint Microsoft and Google project artificially introduced a web latency of 400 ms, which cost the two corporations 0.76% of their revenue, amounting to $175 million in 2020.

Content placement is another vital decision affecting latency. Multiple solutions were proposed in [61] and [62], introducing cache, network proxies, and the hierarchical placement of contents to servers that can reduce latency to a certain extent. However, in the case of a missed cache or uncacheable contents, such methods are not feasible. The most effective technique for reducing latency involves the placement of applications and services in the vicinity of users using cloudlets [63].

Cloudlets experience processing and queueing delays, which can significantly affect the response time of an application, when numerous users avail of a set of services from a single cloudlet. In [10], scaled a cloudlet to multiple cloudlets, in which mobile users can offload compute-intensive tasks to a cloudlet that resides in a low workload, thereby reducing processing and queueing delays and improving response time.

Cloudlet networks are solutions that leverage the issue of scalability with cloudlets. The study in [48] presented a new task assignment offloading technique that performs task assignment among cloudlets and used latency as a task-assignment metric among the cloudlets. This technique can protect a single cloudlet from being overloaded and help achieve the superior QoS promised by cloudlets.

In a nutshell, the significance of cloudlets can be witnessed in latency-sensitive applications, such as real-time cognitive assistance, AR, face recognition, and location-aware online games, in handheld devices. Varghese in [64] tested a Pokemon game in which locations can be updated constantly using GPS coordinates. Users must collect geographically distributed Pokemons and train them virtually for battles, locate the movement of peers, and create high-value profiles. The game resides in the EC2, which is a cloud that is approximately 3,500 miles away from a user located in Belfast, Northern Ireland. Varghese witnessed the game crash four times while launching, which can severely affect user experience. However, the introduction of cloudlets in the same environment can reduce latency, facilitate users offloading of compute-intensive tasks with a strong Wi-Fi connection, and improve the battery life of handheld devices.

B. S AND IM IN CLOUDLETS

The NaaS is a successful model, in which a cloud can provide applications and services to end users, such as virtual private networks, on-demand voice/videos, mobile network augmentation, and so on. Such services are offered by ISPs and telcos, as user interest at the personal and commercial levels increased drastically. Cloudlets have the potential to offer services with low latency, efficient bandwidth utilization, and security compared with clouds. Figure 4 highlights cloudlet communication and network services.

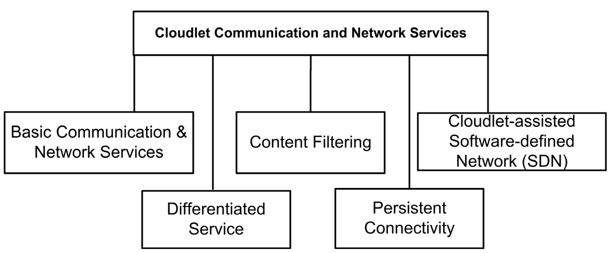

FIGURE 4. **Cloudlet communication and network services.**

1) BASIC COMMUNICATION AND NETWORK SERVICES

Cloudlets can provide basic services, such as voice and data services, which are the most common services offered by service providers but remain the main revenue earners [65]. In addition, cloudlets can be used in many other services, such as website and content hosting, service identification, firewall security, application streaming, mobility management, and virtual private networks. Cloudlets reside in users locality and can guarantee low latency, high bandwidth, and crisp response at a reasonable price and with noteworthy advantages [66]. Whether deployed alone or in conjunction with an enterprise cloud, cloudlets are equally beneficial. In any setting, content filtering and first-line security can be achieved.

2) DIFFERENTIATED SERVICES

The existing Internet environment can offer the best services, and getting differentiated service over the Internet is rather difficult and expensive. Cloudlets use Wi-Fi connections and have sufficient space to accommodate new services, thereby facilitating users attainment of desirable QoS requirements to meet rising demands. Although cloudlets have numerous utilities, one of the challenges involves the identification of a feasible location where a cloudlet can be deployed [67]. In a standalone environment, a cloudlet is positioned within a users vicinity, where it can be accessed by the user with ease. However, if a cloudlet is deployed in combination with an enterprise cloud, then the cloudlet will be located between the cloud and user. An ISP can identify a feasible location for deploying cloudlets. In this setup, a cloudlet resides between a user and cloud and acts as an intelligent device to monitor Internet traffic and provide desirable QoS requirements, a strong signal, and mobility management to end users.

3) CONTEXT FILTERING

Context or information filtering involves allowing or restricting certain types of services for users, machines, or applications. For example, in packet filtering, in a network or the Internet, the environment blocks or allows packets based on address, ports, or protocols [68]. In application filtering, a network-based application firewall can be deployed at the application layer of a protocol stack, such as a proxy-based or reverse proxy firewall. Such services aim to add something new to the Internet core network, which is too saturated to accommodate new products and services [69]. Hence, the industry and academia paved the way for overlay networks. Cloudlets can be placed intentionally in users locality to provide the aforementioned services, thereby allowing the addition of new products and services to the core network without adding application layer overlays [70].

4) PERSISTENT CONNECTIVITY

Cloudlets in hostile environments, such as battlefields or terrorist snap check operation regions, where poor or no technological infrastructure exists, will experience DIL connectivity. Accessing clouds in such regions is difficult and will produce suboptimal results. Cloudlets can overcome this problem by acting as a proxy Internet connection and offer services in the absence of an enterprise cloud [41]. Moreover, the use of a cloudlet as an intermediate data processing node can restrict unwanted traffic and reduce the load over the cloud. Content filtering and local data caching of compute-intensive tasks, such as pattern matching, image processing, or contextual information, by caching cloudlets would be highly beneficial. Cloudlets can also be deployed as personal area networks or LANs, acting as hotspots to offer network and application services to connected users. This approach is suitable for handling resource-poor handheld devices, such as mobile phones, PDAs, and tablets, using

Wi-Fi signals to avail improved bandwidth and crisp response despite using GSM signals.

5) CLOUDLET-ASSISTED SDN

An SDN aims to separate and place network administration, control, and decision making from the router hardware to another location, which is quite difficult in the existing Internet architecture, because the Internet is too saturated to add new devices and services [54]. However, this goal can be achieved through an MCC, specifically, cloudlets.

In the current Internet core network, switching, routing, network administration, network convergence, and control are performed by the router hardware, causing it to become overburdened. Network administration, network convergence, and control can be assigned to cloudlets, but switching and routing are performed by the router hardware [54]. This philosophy may allow network resource provisioning and compute-intensive decision-making algorithms to shift to cloudlets [44]. Similarly, the presence of a VM in a cloudlet incorporate the responsibility of virtual routers and switches via a hypervisor [61].

Emerging technologies encompass the idea of ubiquitous computing, leveraging the power of devices and reducing their size. The IoT interconnects several devices to communicate with one another over the Internet and IoE, where devices are not only interconnected physically but can also read one another. Both technologies are intentionally designed to connect devices across the globe to form an ad hoc continually progressing network [45]. Applications such as the Internet of vehicles [71], the Internet of sensors [72], and the Internet of mobile phones [25], are ubiquitous. Such technologies and many other are advancing toward a future interaction paradigm shift known as 5G [64], which can create data in bulks requiring increased bandwidth and considerable processing. Cloudlets at the leading edge have the potential to meet the emerging needs of future technologies.

C. ENERGY AND BANDWIDTH EFFICIENCY IN CLOUDLETS

Emerging mobile interactive applications, real-time applications, and GPS applications require increased memory and considerable processing capabilities. Mobile devices improved substantially over the last decennium but lack high processing power to perform computationally intensive tasks, as they consume excessive amounts of energy, thereby causing battery drain [49]. However, cloudlets can address these issues effectively. The existing study [73] classified applications into three major categories, which can benefit from Cloudlets, that is, computationally intensive, data intensive, and communication intensive. Devices that handle computationally intensive tasks suit computation offloading techniques via cloudlets, whereas devices that deal with data-intensive tasks benefit from data-staging techniques with cloudlets. Meanwhile, devices that handle communication-intensive tasks can benefit from the network as a NaaS model through cloudlets. The computation offloading taxonomy is shown in Figure 5. In computation offloading, a mobile user offloads a compute-intensive task partly or completely to process over a cloudlet and receive results [74]. This technique protects resource-limited devices from battery drain and enables them to execute tasks that are beyond their capabilities. Computation offloading is used in remote execution [75], load sharing [76], and cyber foraging [48], in which tasks that require extensive processing are transferred using thread offloading, component offloading, and application offloading.

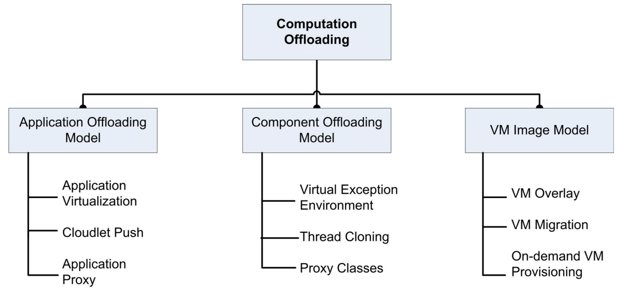

FIGURE 5. Taxonomy of computation offloading.

An application residing in a cloud or cloudlet has a distinct computation offloading mechanism. Computation offloading to a cloud relies on an Internet connection and cloud resources, along with policies that pair mobile devices with clouds. The study in [9], further illustrated the concept of cyber foraging [22], which bridges mobile phones and cloud computing. The authors work categorizes computation offloading into three major parts, namely, application offloading, component offloading, and virtual image migration, as depicted in Figure 5.

Application offloading is the simplest method, in which an entire task or application is assigned to a cloudlet for processing [77]. In the component offloading technique, a part or thread of an application is offloaded to a cloudlet for processing [78]. Meanwhile, in VM image offloading [79], a cloudlet infrastructure based on the deployment of a VM image over a cloudlet provides applications and services to mobile users [80]. This model enables a cloudlet to provide as many VM guest environments as necessary, scales the cloudlets, and helps users find cloudlets that are compatible to their needs without increasing the complexity of the architecture.

The aforementioned offloading methods are useful but complex and experience several challenges that must be addressed. However, application offloading includes the challenges of cloudlet discovery, process migration, context gathering, and remote execution control. Computation offloading via an application offloading technique does not require scheduling and process synchronization overhead [81] and [59]. Moreover, it consumes substantial energy in a computationally extensive application that takes continuous inputs from a mobile device [68]. Proximate cloud, [11] presented the concept of computation offloading through application virtualization, cloudlet push in [82], and application proxy in [32].

In component offloading, an application is statically or dynamically divided into multiple components by a developer while the application is designed over the system at run time. The component that requires heavy processing can be offloaded only to a cloudlet [83]. This model is relatively successful for resource-poor devices in terms of energy efficiency but fails to handle the offloading environment owing to the interdependency of threads [50]. This technique can address the synchronization and scheduling overhead of resource-poor mobile devices. Other complexities include remote execution control, context gathering, thread migration, and application partitioning. The component offloading model discussed in several studies includes the virtual execution environment [84], thread cloning [85], and class offload [86].

The VM offloading technique is energy efficient, because it provides a mechanism for offloading compute-intensive tasks to a cloudlet. Several studies presented different types of VM offloading techniques, such as the VM migration model presented by Cardellini in [87], VM overly and on-demand VM provisioning model by Echeverria [40].

Cyber foraging [88] is intentionally designed to use remote resources for extensive computational tasks. Three important points must be considered when conducting computation offloading, that is, (a) where to offload, (b) when to offload, and (c) what to offload. Where to offload illustrates the location of the task to offload. A task may be offloaded to a remote cloud or cloudlet/server that resides in the vicinity of a user. When to offload involves whether to offload statically or at run time. Offloading at run time is quite complex, and one way to deal with this strategy is to partition the code manually or automatically and run it on a mobile phone or surrogate machine. However, run time offloading includes the challenge of optimizing energy efficiency, performance, and network usage, which should be considered when offloading [89]. Moreover, offloading options vary, such as applications, methods, threads, full programs, or a combination of options.

A distributed execution application framework is presented in [51] in which a compute-intensive code is offloaded to a cloudlet or cloud at run time or a mobile application is synchronized with another remotely executed application over the cloud. This technique encourages the live migration of a mobile application to cater to compute node mobility.

In the current technologically competitive market, all major cellular service providers have their own voice interactive assistant. Google Now, Microsoft Siri, and Nokia Cortana are the frontrunners in the race. Voice assistants are intentionally designed to promptly respond to users queries [53].

In speech recognition applications, contact search involves two stages, that is, (a) speech recognition, in which a user query is transformed into a search query, and (b) actual content search. If both stages are performed locally on a mobile device, then the user will receive an undesirable response. Hence, the usability of an application may be questioned to a certain extent, which may involve resource-poor mobile devices. Speech recognition is an important task that requires a large amount of processing power and memory and quick response time. Computation offloading addresses these issues where the user query is preprocessed and then the preprocessed recording is offloaded to a cloud. Finally, a string representation of the query executed in the data center is received [84].

D. INTERACTIVE APPLICATION IN CLOUDLETS

User-centric technologies are highly beneficial and reliable. Future interactive technologies, such as AR, intelligent video acceleration, connected vehicles, VR, IoT gateways, and other emerging technologies, will significantly improve QoE subject to network support for high data rate and low-latency computations. The case of AR as a future interaction paradigm is taken as an example. AR is a combination of real-world views and computer-generated sensory inputs, such as sounds, videos, graphics, or GPS data. AR can improve user experience in point of interest (POI), such as city monuments, skyscraper designs, or museums, in which users can use their mobile phone to capture such POI [40].

The AR application produces output on the basis of device location or POI and additional information for user experience. The application must be aware of the users position and the direction he/she is facing via a positioning technique, camera, or both. When the users position changes, the application information likewise changes, and the application generates additional information in real time. In this scenario, cloudlets are more beneficial than clouds, as all the information related to the POI will be localized and not needed beyond the POI. Figure 6 presents AR services using the MEC cloudlet. In the modern world, mobile phones are largely used for interactive applications [90], such as online chess games. Such an interactive application requires huge computational capabilities when the user makes advanced moves. When image matching, users typically retrieve images and compare them with a large pool of images, which is a compute-intensive task [32].

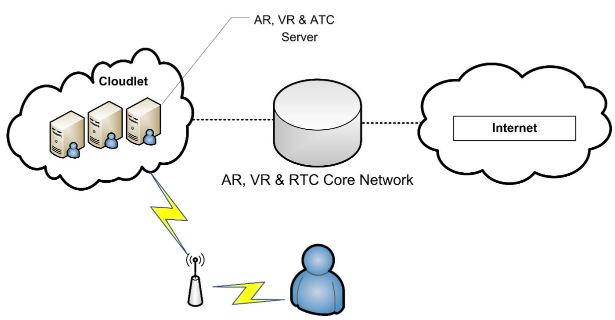

FIGURE 6. **Cloudlet architecture for AR applications.**

Individuals and enterprises may fancy house designs, interior designs, or product designs using a computer-aided design software on a mobile phone, which also require heavy processing. Floating-point calculations and AR applications belong to the interactive application category, which requires intelligent and heavy-duty processing machines.

TABLE 3. Summary of cloudlet challenges and future research directions.

S.no	Cloudlet Challenges	Future Research Directions
a.	• Designing a service centric model	• Wireless network / SDN implementation
b.	• Service migration	• Standardizing interfaces
c.	• Reliability	• Improving programmability of interfaces
d.	• Discovery of Cloudlet nodes	• Scalability planes
e.	• Managing multiple administrative domains	• Benchmarking services
f.	• Deploying services and applications over cloudlet	• Robust migration services
g.	• Load balancing over cloudlets	• Task migration between multiple nodes
h.	• Synchronization of multiple cloudlets	• Resource allocation and release

Handheld devices have yet to achieve such specifications [33]. A real-time video streaming environment using cloudlets and enterprise cloud vendors, such as Google, Amazon, and Azure, was deployed [91]. The authors findings highlighted the importance of a cloudlet, resulting in low packet loss, small delays, and improved throughput, which are the lifeblood of interactive applications.

File editing, video streaming, and collaborative chats are three interactive applications that users access over clouds. In file editing, complete or a portion of data from a file are downloaded to a local cloud, edited, and uploaded using a remote connection. File editing is often used for editing Facebook user profiles, altering databases, and reducing the map algorithm in the Google framework.

Video streaming involves mobile users accessing videos stored in a cloud. Video accessing inherits all the problems associated with handheld devices discussed in Section 2. However, if a video is cached on a cloudlet, then the user will discover the cloudlet and directly stream the video in the presence of a strong Wi-Fi connection.

In collaborative chats, multiple parties can exchange messages while connecting to a cloudlet. All mobile users register to the cloudlet, which advertises the available users to chat with. In this scenario, users can negotiate their security and QoS needs via a cloudlet before accepting collaborative chat requests. In distant cloud [92], deployed a testbed to critically examine the performance of a cloud and cloudlet in file editing, video streaming, and collaborative chats and concluded that the cloudlet outperforms the cloud and reduces latency and increases throughput.

V. CLOUDLET CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Cloudlets have many advantages, as discussed in the previous section. However, they face numerous challenges, such as scalability and coverage region interoperability, in terms of deployment. The authors in [11] and [12] highlighted several cloudlet limitations. Mobile users can access cloudlets via a Wi-Fi connection that works in a confined region. Cloudlets can provide continuous service, but devices located outside the Wi-Fi range will not benefit from the cloudlets [40]. Scalability is an attractive attribute of clouds and other emerging mobile computing systems. However, cloudlet scalability is limited to cloudlet discovery when multiple cloudlets are operating in the same vicinity and subject to the financial conditions of cloudlet providers and their resource provisioning mechanism and the capacity of the Wi-Fi connection to support a limited number of users, thereby making such scalability questionable. Table 3 presents the major challenges of cloudlets and future research directions.

VI. DISCUSSION

This section discusses the role of cloudlets in emerging technologies and how cloudlets can support heterogeneity, achieve resiliency, and reduce vulnerability factors. The emergence of distributed clouds in the form of cloudlets and edge computing will revolutionize the technological landscape of modern applications. These major advancements are expected to focus researchers attention to the cloudlet application domain. Smart systems based on IoT, such as smart city, smart health, smart transportation, and so on, are converting traditional large cities that require efficient resource management into smart cities. However, the deployment of smart infrastructure is expensive, technologically complex, and challenging. Table.4, summarizes the challenges of IoT-based smart systems and the potential of cloudlets to support smart system deployment.

Cloudlet-based computing is developing rapidly owing to cloudlets ultra-low latency, high bandwidth and QoS, and other inherent characteristics. The nature of emerging applications demands crisp response, high bandwidth, and low latency, which cloud computing cannot promise. The Internet is expected to connect billions of devices in the near future, which will require security, data analytics, and efficient resource management. Cloudlets can be a game changer in this scenario. Table 3, highlights the challenges of cloudlets and future research directions that can provide a firm foundation for research on edge computing and distributed cloud computing domains.

A. SUPPORTING HETEROGENEITY, RESILIENCY AND LOWERING VULNERABILITY

Cloudlets can substantially support heterogeneity by allowing different software applications and hardware to interact with one another. In circumstances such as disastrous recovery situations, different teams work in collaboration, in which each team possesses a different set of devices with installed software. The recovery process can be seriously affected by

TABLE 4. Challenges of smart system and cloudlets support for deployment.

S.no	Smart Systems use cases	Common Challenges	Cloudlet Support	Methodologies
1.	Smart City [19], [54], [68]	high bandwidth	computation	- VM/Containers - IaaS, PaaS, SaaS - Processing on demand - Context as a Service
2.	Smart Health [93], [94]	DIL Connectivity	storage	- caching
3.	Smart Transportation [32], [66], [80]	resource constraint	control	- deployment - security - mediation - actuation
4.	Smart Oil Refineries [26], [37], [95]–[97]	low latency	acceleration	- NFV - SDN - GPU
5.	Smart energy/power grid [79], [98]–[101]	reliability	networking	- bluetooth - IP, TCP, UDP - WAN

interoperability issues. VM-based cloudlets can overcome the issue of interoperability by providing a flexible architecture, in which a VM can accumulate and separate the guest environment from the cloudlet host environment according to user type. However, in general, resolving heterogeneity problems completely is a complex task. Cloudlet resiliency can be achieved by strengthening proximity. Cloudlets can providing service in the absence of the main cloud by slightly transforming the cloud application. The offloading of mobile users to the main cloud is a relatively simple task, as its backend is encapsulated by a VM. However, the challenge involves ensuring the existence of a mechanism for selecting an offloading location that fancies nearby cloudlets and that the cloudlets have a copy of the necessary VM. Alternatively, cloudlet-VM synthesis [34] and dynamic cloudlet provisioning [102] can also highlight how cloudlet resiliency can be achieved.

Cloudlets can reduce vulnerability in case of DoS attacks and wireless jamming with physical-layer mechanisms, such as frequency hopping and spread spectrum. The wise selection of such parameters will create unfavorable conditions for DoS attacks. A cloudlet designated in the vicinity of a user, ideally within a single-hop distance, using ultra short-range technology requires a very high workload for a successful DoS attack. In this case, jamming from closely located sources, such as mobile phones, is a potential threat. If the coverage region of a cloudlet-operating area is large, then the jamming radius around mobile devices can be physically secured, thereby preventing jamming in the environment. The single-hop proximity of cloudlets can also prevent multihop threats.

B. STATE-OF-THE-ART SMART CITY

Thousands of cameras, sensors, visual devices, rich interactions, and other online information sources can generate terabytes of data in no time [103]. Finding and tracking relevant occurrences via video surveillance are complex task. The addition of surveillance staff will not necessarily help. Attention can slip when the contact or interaction load becomes extremely high. Real-time situation awareness is crucial in many city surveillance tasks, but network and video processing can become needlessly bogged down by irrelevant data processing and video monitoring. Traditional non-contextualized video recognition techniques [91] cannot be employed in highly valuable and complex online situations, such as a live city environment [96], compared with a platform that can think proactively to detect, select, and track only relevant video streams in surveillance tasks [104]. In such a platform, only a fraction of the relevant video stream from a massive set of videos will be handled.

Mega enterprises, such as Google, Nokia, Microsoft, and others, are seeking solutions to complex problems, such as traffic monitoring, speed and running, and crowd congregation. Such enterprises work extensively on video analytics by leveraging machine learning, pattern recognition, and behavioral knowledge to find relevance in huge data and video content. Nokia MEC [54] and Microsoft Siri are frontrunners in this race.

Besides video streaming and surveillance, other live sensor data can help a smart platform predict the evolution of relevant phenomena [105]. Traditional GPS data allow the tracking and anticipating of field unit positions. Furthermore, improved situation awareness in surveillance applications can be leveraged by the platform to anticipate accurate video stream selection. To enhance situation awareness for users, the platform can prioritize streams for the anticipated relevance. Resources can be allocated based on application needs and by cutting off irrelevant streams and ensuring persistent connectivity to needy users. Video analytics (e.g., streaming and surveillance), pattern matching [92], image recognition, crowd congregation [100], and GPS tracking are rich technologies. However, such technologies require massive computational power, high bandwidth, and the large scalable integration of numerous technologies. Moreover, their operation is beyond the capabilities of existing portable or handheld devices. One solution to this problem is to provide access to the several thousands of devices in a smart city to a cloud; however, suboptimal connectivity, high congestion, and limited bandwidth will affect and degrade performance to an unacceptable level.

Cloudlets introduced in such environments can filter unwanted traffic over localized clouds, thereby allowing only necessary data to be uploaded to the cloud, which can protect the backbone from needless congestion. The operation and interconnection of such devices through a strong Wi-Fi connection can boost the performance of devices, applications, and services to a satisfactory level [106]. Additionally, cloudlets can improve trust and risk factors when technology is used to ensure the safety and security of the public. Cloudlets can make the objectives of a smart city realistic and achievable. Table 4 presents the challenges of a smart system and cloudlet support for smart system deployment.

C. CLOUDLETS IN EMERGENCY AND MILITARY APPLICATIONS

Cloudlet applications are not limited to certain locations and are continuously developing technologically. Cloudlets can help in areas with no available technological infrastructure, such as military operations in hills, desserts, or the sea. Cloudlets can also be deployed for short periods for commercial purposes and in disasters, emergencies, and remote areas. The military uses a variety of technologies, such as WAN links based on satellite and air support, to coordinate their operations. A military network operates on a two-level cloud computing architecture consisting of a data center, namely, the cloud, and multilevel micro data centers, that is, the cloudlets. This architecture is used as a middle tier between the cloud and the users. The architecture takes input from the users, in this case, soldiers, processes the input over the cloudlets, then sends the input to the cloud for further operations [82].

Through cloudlets, the military can achieve network resilience. The cloud will store the main VM image on its server, and all the associated cloudlets will store their copies of the VM images. In the case of a disconnected main cloud, the commander will send their requests to a proxy VM server, which will relay the requests to the cloud [107]. In a situation in which a node is connected to an enterprise server, a cloudlet acts as a shield to block an imminent DoS attack to the server, and only a physical attack will be effective. However, if the node is located far from an intermediate node, then it will be vulnerable to DoS assaults, such as wireless signal jamming. To protect their cloudlets, the military must employ a cautious and defensive approach. Death of distance is common in cyber warfare and describes the issue of mobile devices located multiple hops from associated devices, which can be easily disrupted [108]. Therefore, the use of cloudlets, which are only one wireless hop away from associated devices, can ensure cloud to mobile convergence while improving survivability. With the technological advancements of the modern age, the military can overcome the challenge of defending their online data from intruders. Spies may be lurking in the military, who can be easily caught when attempting to access a tightly secured level 1 data center. However, hackers can stealthily access level 2 data centers with weak perimeter security [79].

Finally, diversity is another issue owing to the lack of interoperability. Different officer teams possess different software and hardware capabilities. Therefore, proxy VMs should be used to in-line different mobile devices together [7]. The VM handles the requests and forwards them to the cloud or cloudlets. Apart from the military, cloudlets are gaining importance commercially. IBM and Nokia Siemens Network recently announced a collaboration to create a MEC platform for running application software. In conclusion, cloudlets are secure and adaptable to all types of situations.

VII. CONCLUSION AND FUTURE WORK

This study concludes that cloudlets can reduce network latency, support heterogeneity, achieve resiliency, and improve response time for applications. Cloudlets bring life to resource-poor devices to compute data and execute communication-intensive tasks that are beyond their capabilities using a computation offloading methodology. Moreover, this study describes the complexity of cloudlet discovery, process migration, context gathering, and remote execution control. Despite these challenges, technological integration for smart city deployment and usefulness in hostile environments make cloudlets highly viable. Smart systems encounter numerous challenges, such as high bandwidth, intermittent connectivity, low latency, and reliability, which can be addressed by cloudlets featuring proximity, high bandwidth, and ultra-low latency. Android applications cannot directly interact with a file system interface, thereby creating a semantic gap between application-level abstraction and hoarding, emulation, and conflict resolution. Thus, this gap should be bridged.

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