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Portable Clouds for Provisioning of Computing Services in Networks with Very Limited Connectivity

Murooj Nadhom
College of Engineering
Swansea University
Swansea, UK

Pavel Loskot*
College of Engineering
Swansea University
Swansea, UK

Marcos Katz
Dept. of Elect. Inf. Eng.
University of Oulu
Oulu, Finland

Frank Fitzek
Facul. Elect. Comp. Eng.
TU Dresden
Dresden, Germany

***Abstract*— In this paper, portable clouds are devised after observing similarities between providing the Internet access to users onboard vehicles and to users in remote resources-constrained communities. In both cases, a gateway connection to the core network is bandwidth-limited and unreliable. Portable clouds are intended to provide applications and services in scenarios even when the gateway link is not available at all for extended periods of time. Portable clouds exploit cache to store contents and provide computing resources locally while the applications are modified to facilitate acceptable QoE. The cache is updated infrequently and only when a fast connection becomes available, or when the contents are physically delivered to the cache using a memory medium.**

***Keywords*— cache; cloudlets; inflight Internet; mobile cloud computing; portable clouds; remote communities**

I. Introduction

Over the past two decades, the Internet evolved from simple static contents sharing to offering interactive dynamic applications where the users can generate and share their own contents. The popularity and reliance on the Internet services is steadily growing. The current efforts focus on extending the Internet services to scenarios where these services were traditionally not available due to difficulties in obtaining connectivity to the Internet core. One such scenario is concerned with the Internet services provisioning to travellers on public transport [1], since the Internet availability affects the passenger experience, particularly during long-haul travels [2]. Another similar scenario (see Table I) is about providing the Internet services in geographically remote regions [3]. In this case, the Internet availability is related to digital inclusivity [4].

TABLE I. Network Scenarios with Limited Connectivity

	Public transport	**Remote areas**
Gateway link	cellular (LTE) or satellite	microwave (802.11) or satellite
Link rate	Low	Low
Link stability	High	Low
User density	High	Low
Maintenance	Easy	Difficult
Powering	Easy	Difficult
Busin. model	Add-on	Subscription

More specifically, passengers on metropolitan transport (buses, light rail, metro subway) may exploit local WiFi networks at stations which often creates a flash crowd problem. However, WiFi networks do not distinguish between the passengers waiting at the station and those who are onboard the vehicle and only transiting. The network access for passengers on long-haul high-speed trains is either provided by sparsely distributed cellular base stations, or by satellites. Aircraft passengers can access the Internet above certain altitude (for security reasons) also by satellites. The Internet access in remote regions is usually provided by long-range microwave links using 802.11 commodity hardware or by satellite links, since the conventional telecommunication networks are not economically viable in these areas due to very low user density and other problems such as the local geography [5,6]. Generally, the satellite links are expensive and the bandwidth is shared by a large number of geographically dispersed users, resulting in low offered per-user data rates.

Even though some technical and many socio-economic aspects of these two scenarios are different, in this paper, we consider a solution that can be adopted to both these scenarios having in common that the Internet gateway either has very limited bandwidth, or it may not be available at all (temporarily or permanently), is very unreliable and/or unstable. We refer to our proposed solution as a portable cloud.

The rest of this paper is organized as follows. We first review previous works and solutions for the Internet access with limited connectivity in Section II. Portable clouds are introduced in Section III. Discussion about the future developments concludes the paper in Section IV.

II. Internet Access with Limited Connectivity

We review relevant solutions that have been proposed or considered previously. These solutions either exploit caching of contents with various cache update strategies [7] (e.g., prefetching, preemptive caching, and popularity based caching), or they modify existing applications to tolerate larger delays (e.g., delay tolerant networking, DTN) [8].

A. Internet for Travellers

Consider first solutions for providing the Internet access in a public transportation. The authors in [7] designed a cache for use onboard public transport vehicles. The passenger requests are aggregated, and if the requested content has not been already cached, the un-served requests are prioritized and fetched at the next station hotspot, and an alternative similar content is offered meanwhile. This design is strongly dependent on

*Corresponding author: p.loskot@swan.ac.uk, +44 1792 602619

homogeneity of requests including the total volume of all requested contents, and their statistics (e.g., a user may get off and not await the request to be served). Another problem is caching HTTPS (encrypted) traffic, and a support for interactivity and dynamic contents. Smart caching and DTN for mobile terminals with unstable broadband connections has been considered in [8]. The cache content at the end-device is optimized, applications are modified to tolerate larger delays, and the connection is used efficiently once it is available.

Downloading contents from a WiFi network to complement off-loading of traffic from the cellular network is proposed in [9]. A collaborative caching among the WiFi access points is optimized assuming a content popularity index in order to achieve the content distribution fairness. A new network architecture that may provide global ubiquitous coverage with terabits per second data rates is contemplated in [10]. The idea of placing base stations on the ocean surface with long-range optical fiber backhauls is proposed in [11]. A mesh network with air-to-air links to deliver the Internet collaboratively onboard the commercial aircraft is investigated in [12]. However, the solutions introduced in [10]-[12] inherently face many implementation challenges that may not be easy to overcome in practice.

B. Internet for Remote Regions

Recently, there has been significant interest to deliver the Internet services to remote areas with constrained resources and a poor infrastructure including availability and quality of the surface access and the electricity grid. The VillageCache proposed in [13] exploits the contents locality to avoid unnecessary uploads of large multimedia contents to core servers via a bandwidth limited backhaul link. The VillageShare developed in [4] modifies the Internet applications to either utilize an unused gateway capacity or to defer the multimedia content uploads and downloads to less busy hours (e.g. overnight). It was observed in [14] (and confirmed, generally, in [15]) that even when the network access speed is increased significantly in remote areas, the user demand will soon exceeds the available bandwidth. A wireless mesh network to be operated in a remote village is designed in [16]. A wireless LAN for a remote mountainous area with a solar power generation for the network equipment was designed in [3]. A wireless network planning, design, management and operation in rural areas in India are considered in [17]. Practical design of a content distribution network (CDN) with caches and pull/push distribution mechanisms for the deployment in remote villages is presented in [18].

C. Mobile Clouds

We discuss mobile clouds [19] in order to contrast their design with the proposed portable clouds. Mobile clouds aim to augment limited computing and storage resources of handheld devices as well as to conserve their battery by off-loading computations into the cloud. Alternatively, the handheld devices may collaborate and form a distributed cloud among themselves to more efficiently share their limited resources. The idea of combining centralized clouds with servers distributed at the network edge was considered in [15]. Cloudlets are located at the network edge aim to support mobility and to lower the service latency by proximity to users [20,21], but they rely on high-speed backhaul and possibly hierarchical caching. Cloud portability is a concept of allowing the users to change the cloud service providers.

In the next section, we introduce portable clouds that are deployed in close proximity to the users, and provide services even when the backhaul is very limited or non-existent. Their design is strongly context-aware, and they offer pay-per-use subscription, content and computing models while aiming to create a new quality-of-experience (QoE) that would be acceptable to the users.

III. Portable Clouds for the Internet with Limited Connectivity

The concept of portable clouds is depicted in Fig. 1. We explain how these clouds are beneficial for providing the Internet services to travellers on public transport as well as to users in remote regions. We also explain how portable clouds are different from the concepts of Mobile Clouds and Cloudlets.

A WiFi access point or multiple access points provide a local wireless access to users. As shown in Fig. 1, both the portable cloud and the end-user device comprises a cache, buffer, CPU and a network manager which controls all other components. These components can collaborate via the access point and the underlying wireless network, so we will not always explicitly distinguish whether, for instance, we discuss the cache inside the portable cloud or the cache within the user equipment. The cache in the portable cloud may be occasionally connected to the Internet via a high-speed backhaul link. However, this situation occurs rarely and outside the normal intended operation of the portable cloud. For instance, the high-speed backhaul may be available when the transport vehicle is at the station (e.g., aircraft is parked at the gate), or it can be implemented as an offline access using physical delivery of contents on some medium (e.g., USB memory, or a harddrive). We assume that both caches are filled and updated with contents only when such high-speed access is provided.

During normal operations of the portable cloud, the buffer queues some of the application requests which are processed as long as a low-speed (and unreliable) Internet connection is available. Such connection is usually realized by a satellite or a long-range microwave link. More importantly, unlike other mobile cloud computing technologies, portable clouds are designed to provide the Internet and computing services even when no connection to the core Internet exists, or the Internet cloud cannot be reached. This is achieved by a suitable cache design, availability of the local CPU and storage, and especially by modifying the existing applications as well as by adjusting the user's expectations (QoE).

Portable clouds are intended to always operate in close physical proximity to users. Wireless interconnection between the end-devices and the access point is provided mainly for convenience to allow for a limited mobility of users about the access point. In transportation scenario, both the users and the portable cloud are located onboard the same vehicle.

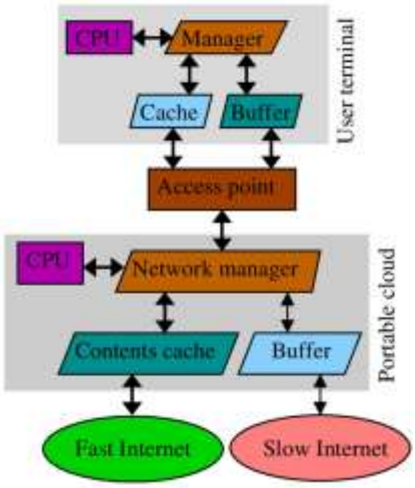

Fig. 1. Conceptual digagram of a portable cloud.

The network managers hierarchically decide how to best serve the application requests. In particular, the manager at the end-device may serve the request using local resources, or it passes the requests up to the manager in the portable cloud. Any requests that may involve larger data transfers (in either direction) would be rejected unless they can be served immediately from the local caches; examples of such requests include transfers of web multimedia and email attachments.

Responding to a content request that cannot be served by the local cache represents an important mechanism in the proposed portable cloud. Such responses must create a reasonable QoE for the users. For example, in order to help the users to adapt their perception of limited contents in the cache as well as limited connectivity, the manager may suggest an alternative content instead. Thus, we do not expect that failed content requests will be deferred and served at some later time in the future. In fact, when a fast connection to update the cache becomes available again, the user is likely not to be interested in that content anymore (e.g., the user disembarks the vehicle).

On the other hand, interactive applications often need the Internet access with some tolerable delay in exchange for lower-bandwidth requirements (e.g., email, social messaging, and e-shopping). These applications will be processed with the aid of a buffer to delay serving the requests until the Internet connection is sufficiently usable again. All these considerations affect the QoE of applications and services for the users of portable clouds.

A. Modifying Internet Applications

In order to understand which applications would have to be modified for use in portable clouds to achieve the acceptable QoE even when there is little or no connectivity to the Internet, we review the most common activities of users on the Internet [22]:

- sending and receiving emails
- viewing Youtube videos

TABLE II. MOST POPULAR APPLICATIONS

Overall Internet	On smartphones
Facebook	Facebook
Gmail	Youtube
WeChat	Facebook Messenger
Tumblr	Google Search
Twitter	Google Play
Viber	Google Maps
Snapchat	Gmail
Telegram	Instagram

- Google search
- Tweeting
- Skype calls
- Tumblr posts
- Photo upload to Instagram

Note that these activities are ranked by their frequency of use and not according to the traffic volume they generate. The most popular applications on the Internet [23] and on smartphones [24] are in Table II.

The QoE for fixed-speed and unstable connections for web browsing, Youtube videos and Google maps have been compared in [25]. It was observed that the QoE saturates with the connection link reliability and available bandwidth. Surprisingly, the bandwidth fluctuations have more detrimental effect on the perceived QoE when the average connection bandwidth is large. The relationship between the connection bandwidth, the link loss-rate, end-to-end delay and the user's perceived QoE has been established in [26]. A survey of the key performance requirements for different applications can be found in [27]. Consequently, we envision the following examples of modifying the standard Internet applications.

- Automated conversion of dynamic web pages with contents usually located on multiple servers into locally stored static web pages.
- Partial upload of contents from popular Internet portals which may be personalized if the users are known beforehand: Wikipedia, Youtube, Quora.
- Partial upload of current news: CNN, BBC.
- Partial upload of popular e-shopping sites which can be customized for a target group of users and with buffering of the shopping requests: Amazon.
- Fully personalized content pre-upload for individual users: Facebook, Instagram, Twitter.
- Buffering of emails and instant messages with email attachments being rejected straight away.

We now discuss typical usage scenarios to illustrate usefulness of portable clouds.

B. Usage Scenarios

The portable clouds are likely to be operated on board long-haul commercial flights. The cache would be updated based on typical passenger profiles (e.g., deduced from the passenger's age, gender and nationality). The differentiated service for higher paying customers may include pre-ordering of the specific individualized contents. Only light applications such as attachment-less emails and instant messages would be served in near real-time during the flight. It should be noted, however, that airlines are negotiating bulk reservations of the satellite bandwidth to reduce the connection price and provide faster access to the core Internet. Additional income may be generated by advertising. Moreover, various thematic contents (e.g., history, entertainment) may be distributed on the USB cards from shops at the airports, or given out by airlines during the flight. Or, specialized software can be developed to download the desired contents onto a USB card for the users while they are still at home.

For users in remote and resources poor areas, the main concern is a lack of infrastructure and the electricity grid. Also the users' expectations what applications and contents they want to use may be very localized and personalized. The only possible upload of contents to the cache is likely to be a physical delivery using a portable memory. However, even when the cache is updated only occasionally, and there is otherwise no Internet connection at all, the perceived access to the Internet contents and computing applications may be very positive. For instance, it may radically change how education is delivered in the communities, and it will also reduce the digital inclusivity gap.

IV. Discussion

We introduced portable clouds to serve the Internet users when their connectivity is very limited, or not available at all (offline). However, there are many practical design and implementation factors that we did not consider such as security, privacy (personal information and data collection), energy efficiency as well as many opportunities to define new business and contents creation models, and to create new applications for the scenarios with limited connectivity. We advocate that web pages should not be only available in mobile versions for viewing on the handheld devices with small screens, but web pages should be also offered in portable (static) versions to support their independent caching and off-line consumption in portable clouds.

Interestingly, we can extrapolate the idea of portable clouds that operate locally with limited or no connectivity at all. In particular, one may start considering larger segments of the Internet to be operated rather independently, while the interconnections between the segments are very limited, unreliable or non-existent. This approach would lead to a collection of the independent Internets. One scenario where this trend can already be observed is the case when a country starts limiting the outgoing Internet connections as part of controlling its national Internet. In the future, we may even expect that part of the sanctions imposed against countries would also involve limiting their main Internet routes. Hence, these considerations have many dimensions and consequences, but they are certainly worth investigating further.

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