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ABSTRACT

Cloud applications are growing more and more complex because of user mobility, hardware heterogeneity, and multi-component nature. Today's cloud infrastructure paradigm, based on distant data centers are not able to provide consistent performance and low enough communication latency for future applications. These discrepancies can be accommodated using existing large-scale distributed cloud infrastructure, also known as Infinite Cloud, which is amalgam of several Data Centres hosted by a Telecom Network. The Infinite Cloud provides opportunity for applications with high capacity, high availability, and low latency. The Infinite Cloud infrastructure and federated cloud paradigms introduce several challenges due to the heterogeneous nature of the resources of different scale, latencies due to geographical locations and dynamic workload, to better accommodate distributed applications with increased diversity. Managing a vast heterogeneous infrastructure of this nature can no longer be done manually. Autonomous, distributed, collaborative, and self-configuring systems need to be developed to manage the resources of the Infinite Cloud in order to meet application Service Level Agreements (SLAs), and the operators' internal management objectives, [8]. In this paper, we discuss some of the associated research challenges for such a system by formulating an optimization problem based on its constituent cost models. The decision maker takes into account the computational complexity as well as stability of the optimal solution.

Keywords

Infinite Cloud, Application Placement, Optimisation, Topology, Feedback, Telecom

1. INTRODUCTION

As cloud computing is transforming the applications, usage patterns, and business models of today, its realization has not yet achieved its full potential. For cloud resources to be ubiquitous and to truly offer computing as a utility, future infrastructure generations will need to be capable of meeting these expectations. New applications having different run times will be highly distributed, run on heterogeneous hardware and software with low latency and high availability requirements. The Infinite Cloud's end-users should be agnostic to where and how their application or content is stored and executed, irrespective of its complexity and size. The cloud capacity-abyss should seemingly, without doubt, absorb whatever is submitted to it. One way to realize this goal and to accommodate the increased plurality of applications, is to augment and diversify the existing cloud capacity beyond infinity through federated clouds and telco networks. Through its distributed cloud resources in a telco's network, an Infinite Cloud introduces an increased latency and compute capacity diversity, and enables network aware applications. In union with the federated cloud paradigm, more diverse sets of resources can be offered and brokered to any cloud application, specific to where its users are, see Figure 1.

With increased resource plurality, new applications, and greater expectations on cloud services also comes new challenges. The vast number of heterogenous resources will need to be autonomically managed with feedback from both external and internal inputs for efficient resource utilisation.The autonomous systems should collaborate holistically to minimise global energy, compute, and network resource usage.

2. INFINITE CLOUD MOTIVATION

Distributed application execution is becoming more seamless, to match their individual performance and latency requirements, different tiers are now executed in geographically distributed Data Centres (DCs). Cloud applications are at an increasing rate being accessed from Mobile Devices (MDs). The boundary between discrete applications and how and when they interact with the users and objects in their vicinity is becoming increasingly opaque. Cloud applications such as those with dynamically generated content and critical control process require today unattainably low communication latency. The geographic separation between end-user and the DC in which the application is hosted introduces unwanted communication delay and jitter. Moreover, due to intermittent cloud capacity availability and latency inconsistencies, the current prevailing smartphone "app" paradigm resorts to executing the majority of an application locally in the MD, as opposed to in the cloud [10].

MDs have limited and scarce compute and reserved energy capacity. MD vendors strive to create an experience of perceived desktop-class compute performance and an infinite energy reserve. This sought-after experience can be achieved through application offloading using the available resources in the Infinite Cloud. Offloading can generally be deemed worthwhile if the compute capacity of the DC exceeds that of the MD and the energy consumed executing the application on the MD exceeds the energy consumed communicating application interactions, graphics changes, and user states, provided that it can be done with a low enough communication latency [9]. The Infinite Cloud provides the necessary infrastructure to offload applications from MDs to proximal DCs where compute resources and power is cheap and is accessible with a low communication latency, [4]. Offloading can either come in the form of remote code execution, or in the form of more immersive cloud applications that behave like smartphone "apps". In the Infinite Cloud, residing applications can be made network-aware by granting them access to information about the state of the entire network and the paths to the users it serves.

With the emergence of Internet of Things (IoT), a large number of devices are being interconnected and connected to the Internet, at a rapid rate [3]. These devices, ranging from keyholes, to flower pots, to windows, to luggage, aggregatly produce and receive a huge amount of data. Between a fair number of these devices exists an ad-hoc and circumstantial sensor to actuator relationship. The sensors often lack any self-coordination in-between sensors of their functionality and location. As a result, the vast amount of data is highly contextually correlated or even redundant. Instead of transporting all that data to a distant cloud DC for analysis, real-time event stream processing at the edge of the network can distill the raw data to dismiss redundant and unwanted information. Similarly, autonomously gathered contextual information about the surrounding environment from multiple proximally located Augmented Reality devices could find it beneficial to share and process that information collectively, in the Infinite Cloud.

3. CHALLENGES

The highly distributed and heterogeneous nature of the Infinite Cloud introduces several interesting autonomous resource management challenges arising from a highly dynamic workload, heterogeneous resources, rapid user mobility, heterogeneous energy costs, and multi-component applications. The holistic objectives of an Infinite Cloud is to ensure that it persistently meets the SLAs of the applications it hosts, while minimising its total resource usage, including energy. It should do so proactively by dynamically placing and scaling applications primarily by means of feedback input of prevailing foreground network traffic, DC utilisation levels, and application workload and user location changes, see Figure 1.

One of the foremost challenges in the Infinite Cloud paradigm is how to manage the highly heterogeneous and distributed resources in a complex system. The sheer size of the infrastructure and the number for management parameters renders a fully centralized resource allocation strategy infeasible [1]. As a result, a decentralised collaborative resource management approach needs to be considered. When reevaluating an application placement decision the systems needs to determine if the energy, compute, network, and latency cost fall short of any of the possible placement possibilities that qualify, for a certain period of time. The systems rate of change determines the duration under which a decision is valid. The number of possible placement combinations and the rapid rate of change means discrete placement decisions need to rely on workload, resource availability, and user location prediction. The system needs to distributedly and collaboratively re-evalute the placement of application components, whenever workload changes for an application, when new applications arrive or are terminated, when applications scale up or down, or when foreground traffic volumes change. The triggers and decisions need to be at the granularity of individual application components, thus arguably distributed. The propagation of the collaborative efforts will thus be bounded by the network's topology and of each application's possible placement alternatives.

The management of complex distributed systems is not trivial [2]. If one placement decision fails to find a solution or is sub-optimal, the effect can have reproductions throughout the system, leading to sub-optimal decisions by peer controllers. Self-oscillations need to be mitigated through feedback control [5] that account for the performance of all of its collaborative peers. The challenge is to construct an autonomous distributed resource management system that is able to self-mitigate and self-heal from individual application, DC, network, and system failures. In addition to internal self-inflicted threats, the systems autonomous components also need be able to collaboratively contain and eliminate security threats emanating from both within and beyond the Infinite Cloud.

4. APPROACH

The topology depicted in Figure 1 reflects the union of a Mobile Network Operator (MNO)'s network and a federated cloud infrastructure and should be seen as an abstraction of the Infinite Cloud as proposed in [4]. The placement and scale of the Infinite Cloud DCs will be heavily dictated by the degree of an MNO's infrastructure virtualisation [12], the degree of convergence of core and access networks, and the prevailing geographic demand for cloud services. Although some bounds can be constructed, none of these properties are not yet defined as forthcoming mobile access network standards and topologies are far from being finalised [11].

Existing 3rd and 4th generation mobile access networks are prevailingly tree-structured [6]. This general structure will feasibly be replicated in future mobile infrastructure generations. Furthermore, the bandwidth availability increases towards a root/source of the network and circadian traffic patterns vary with distance to the source nodes. Similarly, communication latency and jitter will decrease with

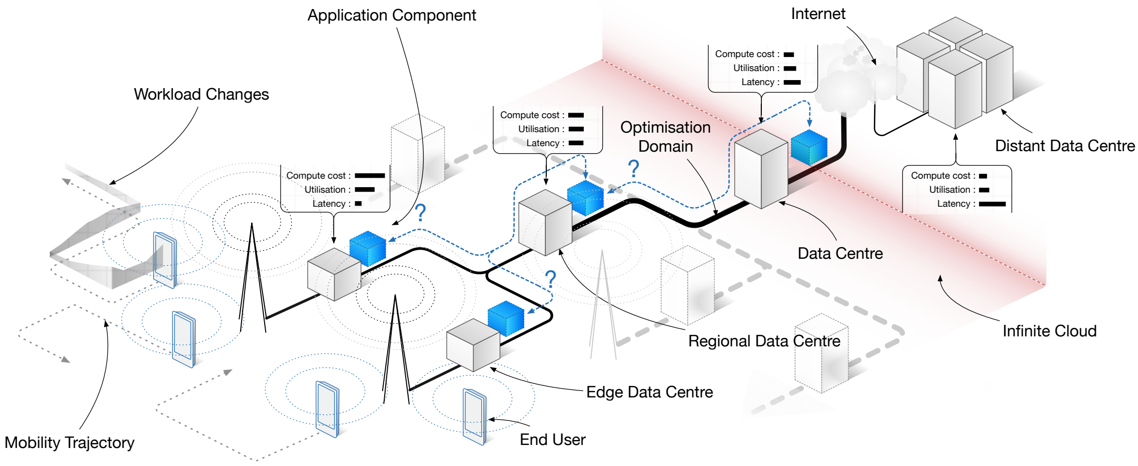

Figure 1: Placement in the Infinite Cloud topology

increased proximity between the DC hosting the application and the application's end-users.

Various MNO IT infrastructure nodes, such as, regional and provincial office facilities and infrastructure hubs are spread throughout the tree's nodes. It is in this existing IT infrastructure that the Infinite Cloud will proposedly be hosted [4]. The compute capacity is feasibly proportional to the aggregate number of users that can access a DC, successively decreasing towards the tree's endpoints. However, given the lack of research into the scale of these DCs, there is very little we are able to specify to this effect. Operational compute cost on the other hand will arguably be proportional to the distance to one of the trees roots, increasing towards the network's end-nodes.

The communication latency of an application is dictated and maintained by the application's relative locations to its subset of *end users*. As the *end-user* mobility from one edge node to another can be highly dynamic, the size and location of applications population of *end users* can vary with time. An application's up- and down-link bandwidth is bounded by the available bandwidth which is shared with time-variant *foreground traffic*, that is assumed to be prioritised in a Telecom network.

A MNO's infrastructure resources are finite, and its objectives are to globally meet the Service Level Objectives of each application and the network's foreground traffic, while minimising its Operational Expenditure (OPEX) and bandwidth usage. Each DC imposes an operational *compute cost*, it is assumed that operational compute cost at the edge nodes of the network is always equal to or greater than to those at the entry points of network. Similarly *bandwidth* cost varies with distance to the edge of the network. An application incurs an up- and down-link *bandwidth* intensity, has a certain *storage* intensity, and *compute* intensity.

One approach is to design a scheduler that minimizes the overall cost for initial deployment and placement through continuous migration of application components on physical machines, intra-DC and/or inter-DC. We intend to achieve this by exploring constituent cost models and relevant feedback metrics that capture the dynamical properties of the Infinite Cloud. The scheduler also takes into account the computational complexity and stability in order to find an optimal solution and to avoid frequent unnecessary migration. The holistic goal is to have a fully autonomous distributed management system that proactively manages all of the Infinite Cloud's resources [7]. The autonomous management system of each constituent component of Infinite Cloud decides where to place and how much resource to allocate to the applications based on reevaluation triggered by new application deployment or change in its workload dynamics.

A federated MNO cloud can contain hundreds or thousands of nodes. As such, all nodes cannot be considered for each placement decision in case of tree structured network scenario. Each search placement for each application is assumed to be limited to the set of DCs that are upstream from the set of *end-users*, and that satisfies the applications upstream and downstream *bandwidth*, *latency*, *compute*, and *storage* requirements. Assuming that an application best serves its *end-users* in a DC one or several nodes along one or several edges leading to its *end-users*, or of equal distance. The search domain is thus relaxed to not include every node in the network. The capacity of the DCs is assumed to be diminishing with distance from the trees root and reach a minimum at the edge of the network, closest to the *end-users*.

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