PROPOSITION OF VOLUNTEER CLOUD COMPUTING

DANY WILSON

1. Introduction

In this current era we can see a shift in how software and hardware are conceived, the end- goals are not the same as they used to be 2 decades ago. This can be attributed to the following, the fact that the Internet speed got a lot faster, by a factor of 1000 (based on a 56kbps connection in 1995, compared to a 50mbps connection today), but also because the hardware performance augmented at a similar pace. Initially in the pre-Internet era, software was written to be executed locally without any network interactions. Then in the genesis of the Internet, the objectives of software slowly shifted to access external resources, thus the apparition of the e-mail and the web-browser. Slowly as the connection bandwidths increased, there was an increased number of possible usage such as online games, content streaming, social-media, etc. Nowadays we can access fully virtualized computing environments within our web-browsers, and this takes us the very genesis of the Cloud Computing era.

1.1. **The Genesis of Cloud Computing.**

The embodiment of Cloud Computing, namely the Internet of Things, can actually be traced back to the vision of J.C.R. Licklider of the *"Intergalactic Computer Network"* [Licklider(1963)]:

> At this extreme, the problem is essentially the one discussed by science fiction writers: *"how do you get communications started among totally uncorrelated sapient beings?"*

This quote shows us the state of electronic tele-communication in the sixties, which is described as being fabric of fiction. There was military but also academic interest of providing an infrastructure that supports long-distance information processing. One of the most interesting idea of this memorandum is best conveyed in this following quote:

> When the computer operated the programs for me, I suppose that the activity took place in the computer at SDC, which is where we have been assuming I was. However, I would just as soon leave that on the level of inference. With a sophisticated network-control system, I would not decide whether to send the data and have them worked on by programs somewhere else, or bring in programs and have them work on my data. I have no great objection to making that decision, for a while at any rate, but, in principle, it seems better for the computer, or the network, somehow, to do that.

This very quote reflects the concept of offloading, not only of information or data, but of computation as a service. In other words that in some case it would be better, given the proper networking infrastructure, to offload the computation and send the data to be processed remotely.

Around the same time the concept of virtualization was being explored in the context of mainframe computers, in order to logically divide the resources between applications allowing them to run simultaneously. Throughout the years, the concept of virtualization broaden and now it is possible to run a complete Operating System on the application level. There is a direct correlation with the coming of the virtualization of hardware and the birth of the Cloud.

Cloud Computing is heavily influenced by the maturity of the Service-Oriented Architecture, and as we said earlier the evolution of the "Internet" with respect to the Web 2.0. That evolution of the Web from 1.0 to 2.0 is marked by the following characteristics, as cited in [O'reilly(2007)]: *[...] services, not packaged software, with cost-effective scalability; [...] data-centric w.r.t. Big Data; [...] users as co-developers; [...] harnessing collective intelligence; [...] leveraging long-tail effect through customer self-service.* We can observe a trend, the concept (web) services (rather then serving only static content) but also how the user becomes the central point of the network as a platform. This entails that components of the Web are becoming interactive services that can be contracted to responds to the users needs, via real-time aggregation of information using Big Data.

Thus the Cloud is the natural evolution of utilizing the network as a platform, through a Service-Oriented Architecture with respect to the natural evolution and maturity of the Web entailing the definition and wide-spread usage of mature Web-Services homogeneous interface (API). *Ipso Facto*, the adoption of pay-per-use business model for the offerings of Cloud Infrastructure.

1.2. **The Cloud.** There have been numerous attempts to try to give a concise or approximate picture of the Cloud Computing paradigm, with respect to its implementation and its different business models. One can review the following, [Zhang et al.(2010)Zhang, Cheng, and Boutaba], [Vaquero et al.(2008)Vaquero, Rodero-Merino, Caceres, and Lindner], [Youseff et al.(2008)Youseff, Butric to name a few. We feel that [Mell and Grance(2011)], [Zhang et al.(2010)Zhang, Cheng, and Boutaba] and [Youseff et al.(2008)Youseff, Butrico, and Da Silva], provides a clear enough picture to represent the current Cloud ecosystem and we will use them to do so.

Cloud Computing infrastructure offers many advantages compared to the traditional on-premise infrastructure and it is why numerous companies consider outsourcing their IT infrastructure to an off-premise solution. Among the most important characteristics that this type of infrastructure offers, the NIST enumerates the following five [Mell and Grance(2011)]:

(1) **On-demand Self-service** *Consumers are not required to interact with any representative of the provider to provision computing capabilities, rather it is automated through the provider's infrastructure.*

(2) **Broad Network Access** *Services are available over standard network infrastructure and through standard mechanisms, enabling different client platforms like cellphones, laptop, tablets, etc.*

(3) **Resource Pooling** *Providers offers a pool of Resources to different clients via a multi-tenant model, consisting of physical and virtual resources that can be assigned and re-assigned dynamically to cater to the clients demands. Clients are only aware, or able to choose the location of these resources with respect to pre-defined geographical regions.*

(4) **Rapid Elasticity** *Resources and services can be provisioned to scale to meet the fluctuations of the client's needs at any time, at any magnitude. The provider offers a seemingly unlimited number of services and resources to the client.*

(5) **Measured Service** *Resource usage can be monitored, controlled (optimized) and reported in a manner that proves transparent to both provider and consumer.*

In this modern day and age, among the major service providers of *The Cloud* we can find the likes of Google, Microsoft and Amazon, to name a few. They provide their services as a 5 different service models:

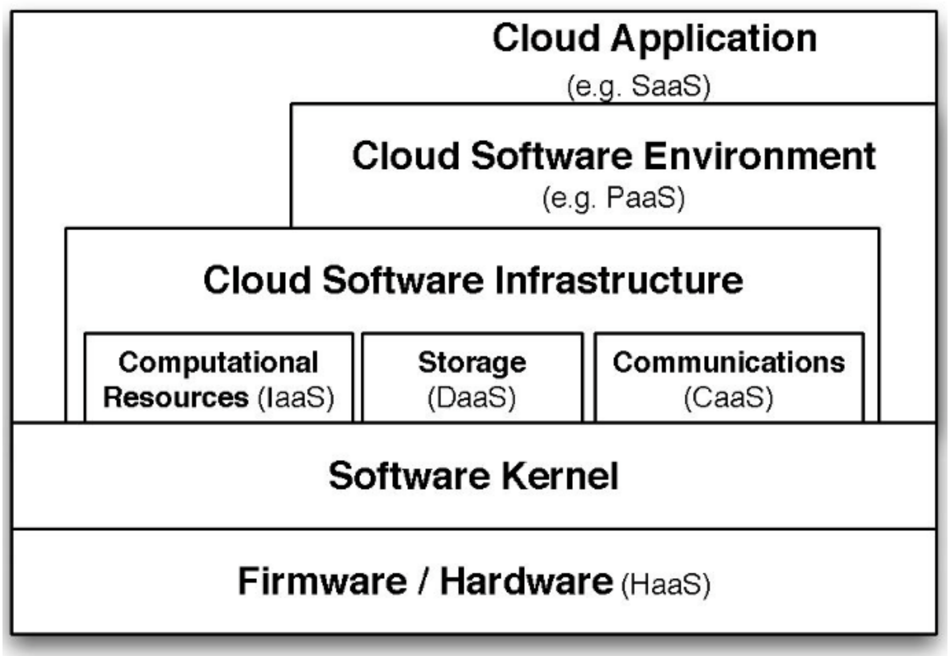


FIGURE 1. Ontological Representation of Cloud

Based on [Youseff et al.(2008)Youseff, Butrico, and Da Silva], we can appreciate the categorization that emerged from their study of the major Cloud Service providers. We will briefly explain 3 of these categories in order to have a clearer picture of where this proposition resides in the grand scheme of the Cloud. In order to do so we will explore the question with respect of the Separation of Responsibilities, via a very concise graphical depiction [Lewis(2011)]:

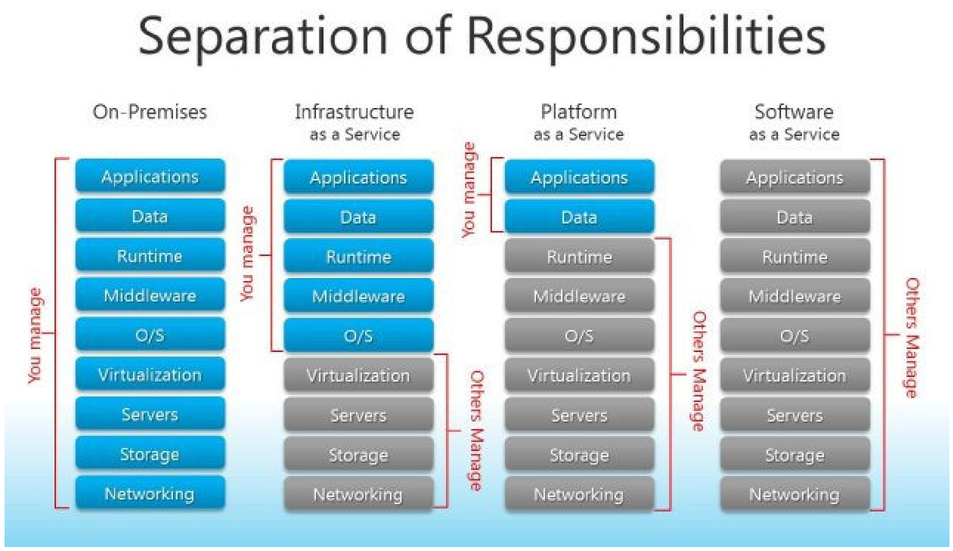


FIGURE 2. Cloud Services w.r.t. Responsibilities

1.2.1. *Infrastructure-as-a-Service (IaaS).* This service model provides, to its consumers, a virtualized environment that represents the full stack, from the hardware-level to the software-level, while taking care of the hardware management aspect. With this model, consumers can deploy any Operating System they wish, and as a matter of fact create the software environment that they deem most appropriate for their use. Since the hardware management responsibility is left out to the service provider, the client can easily augment or reduce the computing power at will to cope with the fluctuation of their demands. Amazon's Elastic Cloud Compute (EC2), or Windows Azure are part of the available IaaS solutions currently available.

1.2.2. *Platform-as-a-Service (PaaS).* This service model, if we refer to Figure 2, to its clients the ability of having to manage only the Application and Data aspect of the full-stack, everything else is managed and taken care of by its provider. Using such a service the client can focus on simply developing their application using the libraries, services and tools supported by the provider, and then deploy it onto the Cloud. Google's App Engine is perhaps one of the most popular example of this model.

1.2.3. *Software-as-a-Service (SaaS).* This service model, the consumer is provided with the capability to use applications (or software) running on the provider's cloud infrastructure, with little to no management capability, as depicted in Figure 2. From a user's perspective application are served as an atomic service, in the likes of Oracle ON DEMAND which offers on demand a customer relationship management application.

Finally we need to discuss the different *Deployment Models* that are offered in the Cloud eco-system. Relying again on the NIST [Mell and Grance(2011)] document, let's briefly present the 4 models:

(1) **Private Cloud** *This cloud infrastructure is meant to be used by a single organization, which can act also as a single provider or a providing partner with a 3rd party or solely as a consumer. Exclusivity is the key here.*

(2) **Community Cloud** *Very similar to the private cloud model, but in this case exclusivity of usage is shared among a community sharing common interests.*

(3) **Public Cloud** *This deployment model is aimed for open use by the general public, and the embodiment of this model's infrastructure is known as a Cloud Provider, such as Amazon, Google, Windows, etc.*

(4) **Hybrid Cloud** *This is the result of the combination of two or more distinct cloud infrastructure (which remain distinct to one another), but are combined using standardized or proprietary technologies to enable data and application portability.*

In the following subsection we will present a fifth deployment model, namely Volunteer Cloud Computing. But in order to provide the proper context for its emergence, lets take a brief look at Grid Computing and Volunteer Computing.

1.3. **Grid Computing.** A very extensive literature exist on this fairly recent paradigm (cite proper sources), and we can define it as being a form of Distributed Computing, where each node is ask to perform a different task, and the aggregation of those nodes workload constitutes the workload that needs to be perform in order to achieve the goal of (computationally) realizing its mandate. A

1.4. **Volunteer Computing.** The @Home paradigm or philosophy beautifully proves how this is realized, and let's look at a simple example the SETI@Home project.

1.5. **Volunteer Cloud Computing.** The concept of Volunteer Cloud Computing is a fairly new one, since as we can see there is no mention of it whatsoever in [Mell and Grance(2011)][Rimal et al.(2009 It revolves around user-provided resources as the building components of the cloud infrastructure, and typically takes place in a decentralized manner for which no single provider is designated, rather the collection of the participants form at the same time the provider and the consumers. One of the driving factors of this topological ideology is to harvest and make efficient use of distributed idling resources to provide a cloud infrastructure, with no real added cost.

In the following section we will review the literature to find out more about the position of Volunteer Cloud Computing with respect to the current deployment models in place, and if any implementation exists.

2. Related Work

2.1. **Cloud@Home.** The first real apparition of the term Volunteer Cloud Computing can be attributed to [Cunsolo et al.(2009)Cunsolo, Distefano, Puliafito, and Scarpa], in 2009 when they proposed the Cloud@Home paradigm. It can be described as a continuation of the @Home distributed computing effort and the merging of volunteer computing and Cloud computing. They propose an infrastructure in which it is possible for heterogeneous computing resources to be connected and to co-operatively provide a Cloud infrastructure, at a cost or for free. Thus this is a leap into monetizing the idle time of the consumer-grade computing resources, to provide a seamless Cloud experience to consumers. Although they provide a very detail analysis of the majority of the factors present in a Cloud architecture, little to no information was released after the publication of a series of more specific papers on the subject,. Last paper that was published, [Distefano and Puliafito(2012)], was indicating that they were actively working on an implementation of their proposed framework, but that was back in 2012. Thus, we will elaborate on what are the characteristics of this project, and try to understand why it seemed to have stop or at least why the driving factors seems less violent as they once were.

2.1.1. *Preliminaries.* The complete bibliography of the project span over 11 papers, which a couple of them are re-publications in different proceedings, journal, and/or conferences. The first paper cathome, presents an overview of the scope and motivation, which we already discussed, but also presents a tentative architecture of what a it could become. What is very interesting here is the presentation of the *Issues, Challenges and Open Problems*, for which they define 6 aspects that will act a mind-map of the problems to tackle along the way, as well as a reminders of the realizability of some more open problems. Let's list them, as presented:

(1) **Resources and Service Management:** *Need for a mechanism that provides it.*
(2) **Frontend:** *Provide users with high-level service-oriented POV of the Cloud Infrastructure.*
(3) **Security:** *Cite different security concerns, not important for now.*
(4) **Reliability:** *Need for redundancy, and recovery mechanisms.*
(5) **Interoperability:** *Need to operate with other Cloud Infrastructures.*
(6) **Business Models:** *Need for QoS/SLA management for commercial Clouds, and also with the open volunteer Cloud framework.*

2.1.2. *Architecture.* Next they present an architecture that responds to these challenges (or requirements) partially or fully, but in a abstract fashion. A picture is worth a 1000 words, thus let's not babble on this much longer and present it:

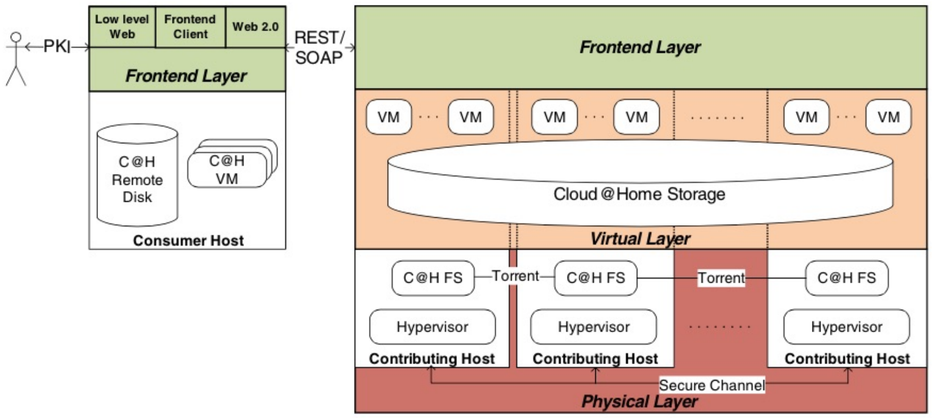


FIGURE 3. Cloud@Home Architecture

We can observe the three-tier approach to organize the architecture: *Frontend Layer*, *Virtual Layer* and the *Physical Layer*.

The **Frontend Layer** is the realization of the answer to the *Frontend* challenge that they proposed in their preliminary discussion of the project. In order to achieve it, they propose to split this layer into two parts, namely the *Server-side* and *Light Client-side*. We can see that they adopt a client-server approach from the user's perspective, and thus we can extrapolate that there is a hint for a centralized mean to deal with *Resource Management* (as a matter of fact in a later paper, namely [Cunsolo et al.(2010a)Cunsolo, Distefano, Puliafito, and Scarpa] and [Distefano et al.(2011)Distefano, Fazio, and Puliafito] they explicitly express the need of a centralized entity w.r.t. Resource Management).

The **Virtual Layer** consist of a consequence to the *Frontend* challenge, or in other words *How to provide homogeneous perspective of a set of heterogeneous resources?* Their answer: through **Virtualization**, which enables us to discard the disparities within the different hardware offered by the participants. This virtualization will take place into what they call the *Execution Service*, and the persistency of the data will be ensured by the *Storage Service*. This service is analogous of the GoogleFS (file system) [Ghemawat et al.(2003)Ghemawat, Gobioff, and Leung which, in a nutshell split files into *chunks* of equal size, which are then distributed of different nodes called *Chunk Servers* (and replicated to ensure reliable storage). Finally there is a *Master Node* that catalogs all the meta-data about the data stored and simply indicate to the user which Chunk Server(s) possess the parts consisting the file requested, thus the user retrieve the chunks directly from the Chunk Server(s). This is a very naive simplification, but it serves to give an overview how such distributed file system can be implemented (in the context of this Cloud Infrastructure), and how from a user's perspective it resembles, as cited in [Cunsolo et al.(2009)Cunsolo, Distefano, Puliafito, and Scarpa]: *a locally mounted remote disk*.

The **Physical Layer** act as the provider of physical resources to the layer above, but also it encompasses all that is required to manage those resources (locally). Also they note

that it is here that the negotiation mechanisms, w.r.t. users contribution and request of resources, should reside and by trickling down from the precedent layers it's policies should be enforced.
Finally this is a brief overview of the architecture that they propose for the Cloud@Home project, but nonetheless sufficient for now. It provides the mainlines to start an analysis, and if required we will in subsequent section to more specific aspect of this architecture as a mean of comparison to the architecture that we propose for our proof of concept.

2.1.3. *Brief Analysis.* We've presented the biggest and most important project w.r.t. a large-scale Volunteer Cloud Computing Infrastructure, now let's recapitulate the important points of this project. First they proposed to a marriage between volunteer and commercially available resources, and on this basis develop a business model that would give the ability to any user to monetize their volunteered resources. Secondly, they proposed a 3-tier architecture that would answer the major challenges that they identified, such as: offering a frontend that enables users to have a uniform homogeneous view of the cloud infrastructure; segregate the resources according to two services (Execution/Storage); and how to manage resources and services within a distributed infrastructure. Finally, we can observe that there is an intention of providing all types of delivery models: IaaS, PaaS, and SaaS.

2.2. **P2P Cloud System.** There was other notable effort conducted with respect to this concept, [Babaoglu et al.(2012)Babaoglu, Marzolla, and Tamburini], albeit presented under a different category one of Peer-to-peer Cloud Architecture. The authors propose and describes the design and prototype implementation of a fully decentralized, P2P Cloud. They present the idea of Peer-to-Peer Cloud Computing, which consist of building a cloud out of independent resources that are opportunistically assembled. It could be built by assembling individual peers without any central monitoring or coordination component. It would provide on-demand scalability, access to computing and storage space with no single point of failure nor central management. Resources are added to the pool of resources simply by installing a software daemon on them. Their proposed implementation is advertised as a fully distributed IaaS Cloud infrastructure.
They differentiate themselves from Cloud@Home by putting emphasis on the fact that it relies on centralized components, while allowing users to contribute, (theoretically it isn?t required). Also, their architecture is fully de-centralized and it doesn't require any central bookkeeping service. Finally, they note that there is no known implementation to date of the Cloud@Home proposal.
The System Model they propose consists of nodes, and these nodes join by installing a software daemon. This software daemon presents two interfaces: a user interface and a node-to-node interface. The API that is exposed by the user interface is similar to conventional IaaS Cloud APIs (such as Amazon EC2 or S3). Nodes are managed by their respective owners in which case it offers no QoS guarantee. It goes for applications failures/crashes; the responsibility is reverted to the users (as would be the case for conventional IaaS Clouds).

2.2.1. *Architecture.* In this section we will briefly present the architecture of the P2PCS, and briefly analyze its key features.

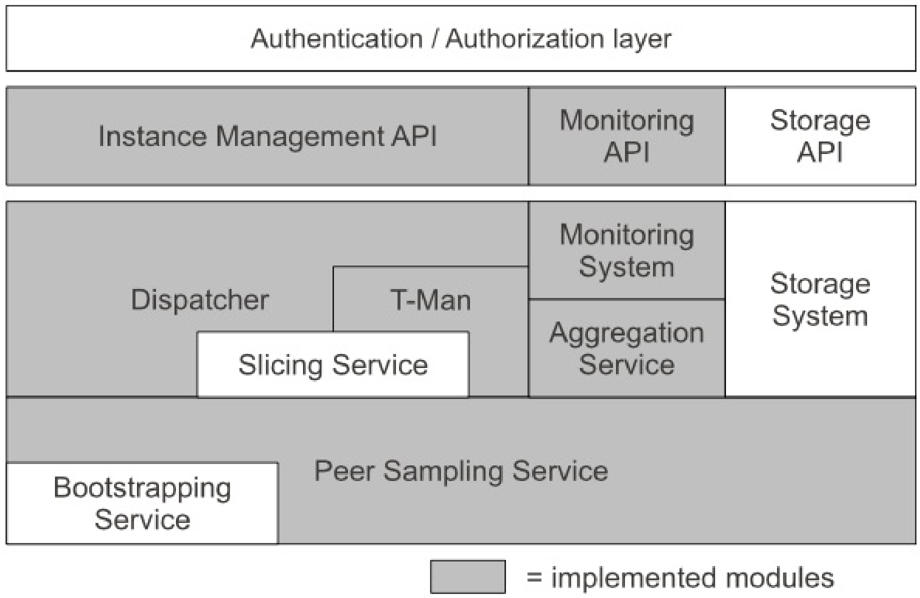


FIGURE 4. P2P Cloud System Architecture

We will briefly present each of the implemented modules (in gray). First the **Peer Sampling Service (PSS)** aims at providing each node with a list of peers to exchange messages with. They achieve this by maintaining an unstructured overlay over the set of peers. It can keep the overlay connected also in presence of churn, by using a simple gossip protocol. It uses a BootStrapping Service to gather an initial set of nodes, although it not implemented yet; the current implementation parses a text file with the IP addresses of the nodes.
Second is the **Slicing Service (SS)**, which is used to rank the nodes according to one or more attributes, it is also used to request slice of the whole cloud according to a user-defined criteria.
Third is the **Aggregation Service (AS)**, which is used to compute global measures using local message exchanges. It allows each peer to know system-wide parameters without the need to access a global registry.
Fourth is the **Monitoring System**, which is implemented on top of the AS, and it collects global system parameters and then provides them to the user. The MS API provides means to start and stop the display of run-time instance informations. In the current implementation it is used to display the topology of the network and the set of nodes of

the slice a node belongs to.
Fifth is the **T-Man component**, which is used to create a overlay network with a given topology, and it is based on gossip protocols.
Sixth is the **Dispatcher**, which is responsible for handling the requests submitted by the user through the high level user interface and translate them into the appropriate low level gossip protocol commands which are sent to the other nodes.
Final is the **Instance Management API**, which contains all the functionalities to create and terminate instances, and also to provide means to list which resources are held by this user.
The implementation was done in Java, using the server-client paradigm.

2.2.2. *Brief Analysis.* It seems to be a dead project, since no updates were done or any changes were made since 2011. This is one of the driving factors of this inquiry. Did support for this project stop out of disinterest by the author, or did its tragic fate is the result of the coming to realization that it is not a appropriate architecture for the Volunteer Cloud Infrastructure?

The cornerstone of this architecture is the use of several gossip-based protocols to achieve such an infrastructure. We need thus to analyze this design decision, in order to assess its effectiveness with respect to particular problem that they are employed to solve.

3. Motivation

The motivation behind this proposal, is to analyze wherein lies (if any) the shortcomings of previous attempts with respect to the problem at hand. Thus we need to formally define the problem, then based on the analysis of these two proposal we will attempt to apply our conclusions in a proof of concept that demonstrate the feasibility of our solution. In this section we will present a formal definition of the problem we are addressing, followed by the justification of the assumptions and the major design decisions.

3.1. **Problem Statement.** The specific nature of the problem of creating a Volunteer-based Cloud Computing infrastructure, lies in the ability with which it aggregates, presents, utilizes, and deals with the intrinsic properties of collaborative distributed system. But we strictly focus on providing an analysis of a fully de-centralized type of architecture, in this case one that operates in an *ad-hoc* manner, or using a peer-to-peer topology.
Second portion of this problem statement is relative to the service model for which we choose to address, the Platform-as-a-Service. It is beyond the scope of this thesis to provide a full and comprehensive infrastructure that addresses the complete spectrum of service models. But it is important to note, the problems identified w.r.t. the challenges of collaborative distributed system are the same regardless of the service model, that this thesis could serve as a starting point towards the definition of this generalized Cloud Infrastructure.
By focusing on PaaS we need to provide a usable and unified API, in the likes of Google App Engine. Thus we need to discuss the requirements of such an API and try to address most of them using state of the art techniques and mechanisms. It is imperative to always keep

the fully de-centralized perspective when analyzing the different parts of this problem. In other words how does the peer-to-peer topology affects the requirements, design and implementation of this API, compared to a centralized PaaS as provided by Google and Amazon.
Third portion of this problem is to answer, based on our conclusions, how well is the peer-to-peer topology, in the context of collaborative systems and Volunteer Cloud Computing, fares against commercially available solutions and what are the incentives (if any) to such a system.

3.2. **Service Model.** We need to situate where, within the already defined ontology of Cloud Computing, our effort will focus. This effort focuses on the Platform-as-a-Service model, conversely to [Cunsolo et al.(2009)Cunsolo, Distefano, Puliafito, and Scarpa] which attempted to propose a solution for all of the service models, and conversely to [Babaoglu et al.(2012)Babaoglu, Ma
that provides a solution w.r.t. the Infrastructure-as-a-Service model.
The driving factor to focus on a PaaS model, is that we intend to propose a solution that does not require any Hypervisor, and thus this solution will operate using Light Virtualization (in the form of containers and more precisely groups [Menage(2011)]). Rather than providing an infrastructure on which different VM can be deployed, we want to abstract this infrastructure by simply providing an environment on which code can be executed, regardless of the underlying infrastructure.
Although this implementation of the proof of concept targets the PaaS model, we will show at the end that the underlying infrastructure that has been developed can be used in the context of SaaS also.

3.3. **Applications.** The C@H project presents

4. Contributions

In this section we will present our novel contributions with respect to previous related work.

5. Network Layer

Upon our literary review we have found a framework that focuses on identifying the challenges and characteristics of collaborative applications over peer-to-peer systems [Bandara and Jayasumana(2013)]. It proposes the following definition of a collaborative system:

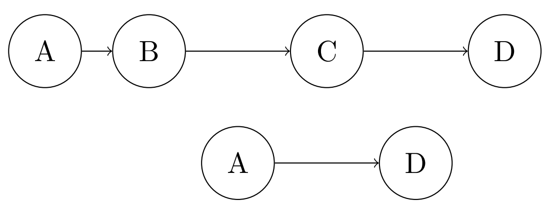
> [...] a P2P system that aggregates a group(s) of diverse resources to accomplish a greater task.

It is important to point out the motivation of this paper is to characterize and formalize the P2P resource collaboration problem and to evaluate the current state of the art with respect to this characterization. They identified 7 key phases that characterizes this problem and we will present them briefly, for a more extensive definition please see [Bandara and Jayasumana(2013)]:

(1) **Advertise**: Each node advertises its resources and their capabilities using one or more formal specification (Resource Specification) over a defined set of attributes.

(2) **Discover**: Nodes may use a mechanism to discover and keep track of the useful specification advertisements from the other participating nodes. This enables to accelerate the querying mechanisms but also to preserve inter-resource relationship information.
(3) **Select**: Provide mechanisms for an user to select a group(s) of resources, that satisfies a formal specification of his requirements, which contains attributes and ranges of acceptable values for these attributes.
(4) **Match**: Provide mechanisms to be able to formally specify inter-resource relationship requirements, to ensure that they satisfy the resource and application constraints, in the query.
(5) **Bind**: Provide a binding mechanism between the resources and the applications, to prevent that two application select the same resources. But also to cope with the dynamic nature of p2p, since a node may not be available at the time of use but was at the time of selection.
(6) **Use**: Utilize the best subset of available resources, from the resources acquired, to execute the application (and all its tasks) while respecting the constraints of both application and resources.
(7) **Release**: Provide a mechanism that allows to release resources in relation to the application demand, and/or the contractual binding (if time-sensitive). That mechanism can also provide means to partially release a resource to enable it collaborate with other applications.

A fundamental concept of peer-to-peer systems, is the **Overlay Network**. It represents the superposition of two networks, one of which could be a physical network with physical connections, and the other a virtual network. Therefore, the overlay network represents a logical (or virtual) connection between nodes, and this enables to represent the absolute path between two nodes, in terms of the logical connection or virtual connection. As an example, if **Node A** is indirectly connected to **Node B** in the physical network architecture:



A indirect connection between two nodes can be expressed in a overlay network as the direct connection between the two nodes, in this case A and D.

Thus it simplifies and abstracts the specificities of the underlying network structure. One the Overlay Network protocols, based on TCP/IP is Distributed Hash Tables (DHTs), we will come back to this after the analysis.

In the following subsection we will present an analysis of the networking capabilities of the two solutions in the scope of the proposed requirements.

5.1. **P2PCS.** The authors of this solution propose a *fully de-centralized peer-to-peer infrastructure*, and we will try to identify the different key phases proposed in the framework although we need to consider the author's caveat about mutual exclusivity of the key phases.

Phase (1) and (2) Advertise and Discover are coupled together in the Peer Sampling Service. But are not exhaustively implemented, by this we underline the fact that they provide no mechanism to advertise the resources that a node offers to the network explicitly. Either using formal means, as proposed in [Bandara and Jayasumana(2013)], or any other means, rather the PSS simply makes a node presence known to the other nodes via a simple gossip-protocol. This protocol grants a node with list of k neighboring nodes, it consist of a *local view* that represent the connections to this node ***since*** the last message exchange (they refer to this concept of performing an exchange of message as a cycle) or cycle. Finally it provides a randomly structured graph, which is shown to stabilize under considerable amount of churn within a very short amount of cycles even with very pessimistic assumptions and no parameter tuning [Jelasity et al.(2007)Jelasity, Voulgaris, Guerraoui, Kermarrec, and Van Steen].

Phase (3) Select is accomplished by the Slicing Service, although they admit that no implementation is provided at the moment of the writing of this paper. They based their design decision on the following paper [Jelasity and Kermarrec(2006)], which presents a very clever algorithm. The problem that this algorithm attempts to solve, is referred as *the ordered slicing problem*, which can be define as follows: *generate a partitioning of nodes in a graph that centric to a given metric.* In this specific case, the graph represents the overlay network and the metric represents a desired property characterizing the application or resources constraints. The authors of [Jelasity and Kermarrec(2006)] assert that this algorithm is easily generalizable, and could be extend to deal with overlapping partitions (multi-attributes query). Finally, for analytical purposes it would have been interesting to see how the implementation of this algorithm w.r.t. multiple attributes would have behave with the complexity of the QoS that are necessary to a collaborative volunteer cloud infrastructure, rather than simply implementing it with a unique metric (the number of desired nodes).

Phase (4) Match is suspected to be realized, if ever, by the SS by a further specification of the query, but this is not clear within the slicing algorithm if it would be able to consider the inter-relations of the nodes in the slices, additionally to the set of queried attributes...

Phase (5) Bind responsibility is accounted by the T-Man gossip-based protocol to build overlay networks with a given topology. It is accomplished by creating a distinct ring overlay of all the peers contained in a specific slice, 1 ring per slice. Thus slices are mutually exclusive. From this perspective, it seems to enforce a good binding policy. Although the question of concurrency, in the context of initially binding the resources to an application rather than another that requests the same resources, is completely left-out. It is a crucial question, since the slices are generated with respect to a metric (composite or unique) which ensures the application's constraints w.r.t. to the QoS. We can quickly observe the fact that the slices may become inadequate if one of (major contributing) resource are lost in a concurrent binding attempt between two *"competing"* applications. Finally, we can conclude that by implementing the slicing mechanism using a single attribute, namely the number of requested nodes, there is no eminent concurrent binding problem because that it would only occur in a very specific case. It would manifest in the form of two or more concurrent requests for which the total requested number of node combined, would exceed the total number of available nodes, but the number of requested node per request would be inferior to the total available nodes. The problem ultimately becomes which application is entitled to have their request fulfilled, with no a priori any ranking mechanism (or reputation mechanism) to draw a fair conclusion?

Phase (6) Use can be interpreted as being manifested by the Dispatcher, which translates the higher-lever API requests into the appropriate low-level gossip protocol commands which are sent to the other nodes. (Not fully clear as to how it manages to accomplish that???)

Phase (7) Release would be accomplished by the Instance Management API, that grant the ability to the user to control the instances it harvests. BUT they express no means of automating the scaling of the resources it possess to respond to the increase of demand or the decrease of the demand. We could extrapolate that the Monitoring System in conjunction with the Aggregation Service could provide enough information to implement such functionality, but nonetheless they fail to make the point.

5.2. **Cloud@Home.** A majority of phases are somehow accomplished by the Management Subsystem. In [Cunsolo et al.(2010b)Cunsolo, Distefano, Puliafito, and Scarpa], there is two important passages that reflect their ideology with respect to the design adopted:

> In order to enroll and manage the distributed resources and services of a Cloud, providing a unique point of access for them, it is necessary to adopt a centralized approach that is implemented by the management subsystem.
>
> The management subsystem is implemented as a centralized subsystem managing the whole infrastructure. Although this solution introduces a single point of failure into the architecture, this is the only possible way to manage resource QoS, SLA, dynamic provisioning, and monitoring because there has to be a subsystem that aggregates information and has to know the condition of the whole infrastructure, there needs to be a coordinator. Reliability, availability, and fault-tolerance issues can be achieved by replicating the management subsystem and its components, adequately managing the consistency of redundant replicas.

In the first quote they assert the need of a centralized entity to accomplish the three key phases: Advertise, Discover, Select, and arguably Match/Bind. This is where we want to verify this kind of assertion, since the previous attempt P2PCS, seems to point in the opposite direction.

The following quote is interesting because the admit the creation of a single point of failure, by consequence of this design decision. Furthermore, they assert that any other type of infrastructure (by design) is inherently inadequate to manage resource QoS, Service-Level Agreements, dynamic provisioning, and monitoring. Their validating argument is the need of an aggregating service that possesses knowledge of the state of the infrastructure as a whole, which is debatable and definitely needs justification for the introduction of a centralized entity, in the context of peer-to-peer systems. Thus, one can deduce from this line of thought that Cloud@Home argue the need for a centralized entity as a solution to these key phases: Advertise, Discover, Select, Match (partially) and Release.

The Management Subsystem is given the task to collect the user's request to assimilate and provide them in the proper format to the corresponding subsystem. The Resource Subsystem is responsible for the resource management, thus it receive a translated request from the Management Subsystem and it is responsible to look through its collection of resources and find the most appropriate selection of resources that satisfies this request. It operates in hierarchical fashion using Schedulers and cluster-type groupings, with a very elaborate load-balancing policy that is extensively described in [Distefano et al.(2011)Distefano, Fazio, and Puliafito]. Finally, one can conclude that the Resource Subsystem is responsible for the following phases: Match (partially), Bind, and Use.

5.3. **Musings.** From these analyses we can draw some conclusions, but more importantly lay out the different point of views that we need to address within our own architecture. The first point of view that seem to emanate from the P2PCS project, *gossip-based protocols are centric to this peer-to-peer collaborative system*, which give rise to the following question:

Are gossip-based protocols the most adequate technology to fashion a collaborative peer-to-peer infrastructure?

The second point of view that is of interest, originates from the Cloud@Home project, and give root to this line of interrogation:

To which extent is the need for centralization, with respect to management of QoS and SLA, dynamic provisioning and monitoring; is accurate in the context of the collaborative peer-to-peer infrastructure? And if provably accurate, is the design for P2PCS fundamentally flawed, do we need to divert our attention to more sensible solution?

These interrogations will be the driving inquiry factors to the elaboration of our architecture, which we will attempt to resolve before presenting it. Thus, the following subsections will deal with providing a rationalization of these line of thoughts.

5.4. **Gossip-based protocols, what is the chat about?** Peer-to-peer systems implements an overlay network, which can be categorized into two broad categories, with respect to their structure and are defined as follows [Lua et al.(2005)Lua, Crowcroft, Pias, Sharma, Lim et al.]:

(1) **Unstructured Networks**:
- Peer organization results in a random graph, which is in a flat or hierarchical topology.
- Querying is generally done using flooding or random walks.
- Locality is not preserved relatively to the topology and the data.
- Supports complex queries.
- Non-deterministic queries.

(2) **Structured Networks**:
- Peer organization results in a structured graph, consisting of dividing the responsibility of the key space among the peers.

- Keys are mapped to a unique live peer, and are assigned to data objects via different means, hashing being the most popular.
- Locality is generally preserved.
- Provides efficient mechanism to query data objects using keys, in the order of $O(logn)$.
- Does not support complex queries.
- Queries are deterministic.

Gossip-based protocols, or epidemic protocols, falls generally into the Unstructured Networks category, with the exceptions of gossip-based protocols like T-Man which focuses on generating a structured overlay network [Jelasity et al.(2009)Jelasity, Montresor, and Babaoglu]. First practical representation of epidemic algorithms in the context of computer science is attributable to [Demers et al.(1987)Demers, Greene, Hauser, Irish, Larson, Shenker, Sturgis, Swinehart, a Since then, the gossip/epidemic protocols have had several praises and criticism, which led to some skepticism w.r.t. it's relevance. Lately a revival of the idea of gossiping protocols emerged, mainly because of the extensive body of work done by Mark Jelasity from the University of Szeged, in Hungary; with respect to its applicability in large-scale distributed networks. A gossiping framework was defined, in [Riviere and Voulgaris(2011)], to circumscribe and represent the various gossiping protocols. Where each node in the system maintains a partial local view of the system, where the partiality is intrinsic to the system size. Interactions within the system consist of pair-wise periodic exchanges of information among randomly selected peers, resulting is eventual correctness of each partial view. The strength of this approach lies in property to achieve local convergence, as driving factor for the nodes decisions, will result to global (or system-wide) convergence. More specifically it provides, as emergent properties of the quantity of interactions involved, a self-stabilization, self-healing and self-configuration characteristics. All of these properties are dependent of convergence criterion, be it local or global.

Epidemic protocols, promises a lot of very interesting properties, lets refer back to [Bandara and Jayasumana(2013)] to make sense of these properties in the collaborative peer-to-peer system context. They make several interesting observations about Unstructured Networks compared to Structured Networks, here's a list of those that we did not already addressed:

1. **Overhead Maintenance**: is relatively low in the case of Unstructured Networks, and moderate in the case of Structured Networks.
2. **Failure/Churn Resistance**: is high in the case of Unstructured Networks, and moderate in the case of Structured Networks.

Thus given the previous observations, and the present one, we could argue the following: Unstructured Networks provides a mean achieve connectivity in highly dynamic environment, thus are robust and resilient to failures. Also they provide querying mechanism that support complex queries, but answer those queries in a non-deterministic manner or as it is often referred as best-effort. Finally, it has unpredictable boundaries on time complexity, thus it is requires to define a maximum on the number of hops, which corresponds to the number of nodes traversed during the walk through the graph and acts as a bound on time complexity. The majority of Unstructured Networks are implemented via gossiping-protocols, although it was proven a very fast and efficient mean to construct overlay topologies that are structured [Jelasity et al.(2009)Jelasity, Montresor, and Babaoglu]. Structured Networks, provide a structural organization of the nodes and the data (in the case of DHTs) which generally preserves locality. It provides a efficient querying mechanism, which is advertised to operate within a $O(logn)$ time complexity (although [Bandara and Jayasumana(2012)] showed that this complexity was theoretical, and that in practice it is more in the order of $O(n)$).

5.5. **To structure or not to, that is the question.** Two of the primary distinctive advantages to using Unstructured Network over Structured Network, are summarized as follows: The ability to generate complex multi-attribute queries and the resilience over very high presence of churn. Thus, we need to understand to which extent these are required in the context of Volunteer Cloud Computing.

If we refer to the current Volunteer Computing efforts, such as the @HOME paradigm, we quickly realize that they use a centralized infrastructure and it has some advantages. One of those is to keep a centralized repository of the host, which provide enough contextual information to quickly restart a failing host. Also, and most importantly this does not require, from the host(s) perspective to preserve any contextual knowledge or structural knowledge of the other nodes from a graph's perspective. This reduce the problem, for the host, to simply reconnect to the centralized node (thus it is only required to know one IP address (of the server)).And we can then notice that Cloud@Home does emulate this notion of a central managing entity, thus it remains true to the @Home paradigm. In our context, since we are aiming at a fully de-centralized architecture, we need to take into account the structure of the network since we do not wish to introduce a centralized entity. This entails the consideration of the dynamism of the underlying infrastructure in the context of collaborative applications, as was the case with P2PCS.

Given the analysis of the P2PCS, which leads us to believe that the dynamism of the network with respect to peer to peer systems, unstructured networks appears the most adequate. Adequacy, in this case, can really be defined given the two advantages presented with unstructured networks. First, it is more resilient in presence of very high churn rate. But can we sacrifice resilience and achieve an acceptable network layer architecture, that satisfies complex multi-attribute queries? Therefore we need to draw the line, and identify typical queries that are necessary in the context of volunteer cloud computing. Because, it is important to distinguish between general collaborative system requirements, and our specific requirements for our application. It can reformulated as the following: *What are the requirements for slicing w.r.t. Volunteer Cloud Computing?* or *What are the minimal requirements for the specification of the resources, that will provide a adequate domain for queries in the context of VCC?*

Slicing is a concept that applies to distributed systems and is concern with the partition of a large set of node in a given graph with respect to attributes (metrics) that are local to the nodes. Thus, complex multi-attribute queries can be represented as a slicing problem for which given a set of attributes (or metrics), with fixed values or ranges

of values, what is the optimal partition of nodes that correspond to this query (with respect to the set of requirements that are formally defined by this set of attributes). As stated above, gossip-based protocols provide means to execute complex multi-attribute queries, as shown in [Pasquet et al.(2014)Pasquet, Maia, Rivière, and Schiavoni]. This favor the use of Unstructured Networks, but simple multi-attributes queries can be performed on Structured Networks given that they use a proper structure, as identified in [Bandara and Jayasumana(2013)]. They show three very simplistic version of a ring-structured overlay:
Separate overlays for each attribute, then depending on the query: choose the appropriate overlay and resolve it. Although, in this case the query are single-attribute, it provides means to query different attributes independently.
Partition the overlay in such a way that it distributes the nodes relative to the pre-defined attributes. Thus, nodes that possess similar attribute values will be closer on the ring. It provides a mean to resolve a multi-attribute query as multiple sub-queries.
Overlay with overlapped attribute space, such that the position of a node is dictated by the juxtaposition of its attribute values in the key-space. This does not allow to resolve multi-attribute queries directly, rather it allows to resolve single-attribute queries that are the product of multi-attributes juxtaposition.
The comparison that they have done shows that current Structured Network solutions are analogous to a tablecloth that is too short. No matter which way you pull on it, which perspective you take to provide a solution, it will uncover another part of the table, thus providing a solution to a specific problem will in turn shed light onto other problems with respect to peer-to-peer systems. One concrete example that they provide is one of MURK [Ganesan et al.(2004)Ganesan, Yang, and Garcia-Molina], which propose to model the attribute space as a d-dimensional torus, where each dimension is representative of specific type of attribute. To deal with the sparsity of the attributes composing real-world queries, since in the initial proposition this results in multiple dimensions that are ignored (or irrelevant), they showed that it could be mapped to a Chord ring and thus reducing the dimensionality. Nonetheless, it results in a lost of locality, given a large dimensionality, and the query resolution cost is now bounded by $O(n)$ with the newly introduced overhead.

We obviously see that it is impractical to use a Structured Network, especially a ring-based one, to solve the Slicing Problem that is present in distributed systems. Also, that an Unstructured Network lacks the ability to resolve queries in a deterministic manner but provides a decent solution to the Slicing Problem and is more resilient to churn. This is an open problem in distributed systems even though it seems to point towards Gossip-Based Protocol as being the solution. scope, we intend only to underline it and present some of the current trends. Thus, to produce a workable proof of concept, we require determinism and single-attribute query will suffice, we will use a DHT named Kademlia. In the following subsection we will quickly present Kademlia, simply to provide a more technical understanding of our Network Layer.

5.6. **Kademlia.** Proposed in 2002 [**?**], Kademlia is a Distributed Hash Table that was designed for peer-to-peer networks. In this DHT, the nodes are assigned 160-bit identifiers, producing a key space of 2^160, and its lookup algorithm uses a XOR metric topology to locate the nodes in a logarithmic time complexity. More specifically, since the keys and the node ID's are of the same length and type, using a simple exclusive-OR between the two results in an integer representing the distance of the key (for which we are searching) and the current node. Also, as a consequence of using such a metric for distance, three properties emerges:

(1) **Triangular Inequality:** given node: A,B,C, $dist(A, B) \leq dist(A, C) + dist(C, B)$
(2) **Symmetric:** $dist(A, B) = dist(B, A)$
(3) **Distance from/between itself:** $dist(A, A) = 0$

It was shown by the creators, that each lookup iteration reduces the distance from the key (for which we are searching) by one bit, and thus a search for a key among 2^n nodes ranges from 1 to n lookup iterations (best case to worst case). Thus, given it simplicity, its determinism and its popularity (*being used by eMule community as a successor to their previous network infrastructure, also by BitTorrent, Osiris SPS, and Gnutella to name a few)*; we decided that it would make an ideal candidate for our proof of concept.

6. Virtual Layer

In this section we will describe the next layer in our infrastructure, the Virtual Layer. Its responsibility is to provide means to make resources homogeneous to the end user. By this we mean that it is responsible to provide a level of abstraction from the specificities of each physical machine (resources). If we quickly review how this is accomplish in Cloud@Home, we notice that they propose using Virtual Machines and Hypervisors to manage them. We can rationalize this idea since they intend to offer a full-fledged Cloud Infrastructure covering the three major services models, and to make it efficient it is necessary to be able to treat each machine (or contributor) as one that can "spin" a VM (whatever it may be). On the other hand, P2PCS took the same perspective, but they are only offering IaaS, rather than the three service models. And there are some advantages in doing so, first it removes the difficulty of deploying on different architectures, since by using this type of virtualization it resides on the application-level. Also it provides the ability to be OS or platform agnostic, because on a Windows machine, it is possible to run a VM with Linux as an OS, and vice-versa. We propose to use a different type of virtualization, namely Light-Virtualization.

6.1. Light Virtualization.

Light Virtualization, also referred to as *Containers*, comes in different flavors, such as LXC, Solaris Containers, OpenVZ, and FreeBSD Jails, the differentiation from full virtualization, is best described with the following picture [De la Rosa and Baxley(June 2014)]:

We can notice that footprint of traditional virtualization is greater, since it requires a Hypervisor to monitor and manage each instances (or VMs) that are executed on this single machine (be it server or personal computer). Whereas the footprint of Containers is less, since it requires no intermediary entity control the instances running on this single machine, but even more important, each instance does not requires to run its own OS.

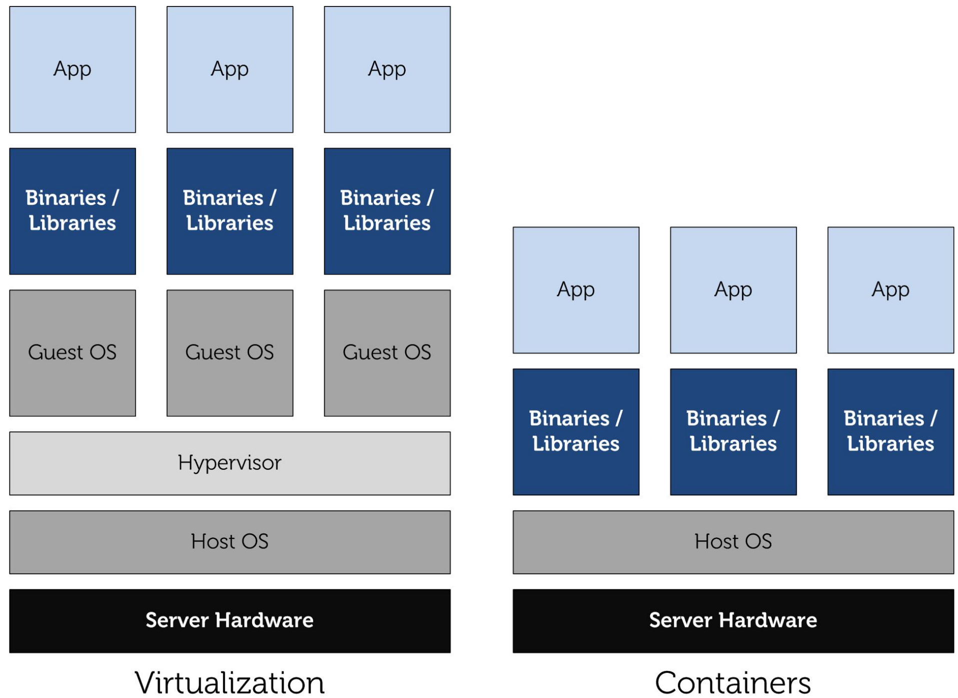


FIGURE 5. VM vs. Containers

Rather it shares the same Kernel, and simply segregates the resources into logical units (or instances). This results in a boot time that approaches mere seconds, rather than just shy of a minute to fully boot a complete operating systems. And this leads to the final important differentiation, how the physical resources are used? In the case of traditional virtualization, the resources are divided and allocated to each VM exclusively; whereas using light virtualization the resources are shared by every containers (although they can be restrained to a certain usage boundary). Although, given this hypothetical situation where one is required to run several instances of the same OS (cluster creation), using traditional virtualization it would still require a Hypervisor and a complete version of the (same) OS running on top of the host OS. But using Containers cluster creation is easily achievable and only requires one single Kernel to be executed on the physical machine.

All of this is possible due to a conceptual construct called *c-groups*, in Linux, or control groups. It was defined as a Kernel patch in [Menage(2011)], and consists of an aggregation and partition mechanism for groups of task (or sets), that contains (within those partitions/aggregations) all their future children. It generates a hierarchy of groups, for which different specialized behaviors can be explicitly defined. The authors admits that in its own, cgroups provides only tracking capabilities for simple jobs. But used with other subsystems (such as cpuset) it can provide additional properties for the groups of processes (i.e.: restraining the execution of a group to a specific CPU-core).

As an example of these emergent properties, LxC (Linux Containers) leverages cgroups to achieve resource isolation and namespace isolation without ever needing any virtual machines. Namespace isolation, grants the ability to isolate running applications completely from the operating system environment such that two applications running into two distinct namespace, albeit not an exclusive feature of LxC. A general example of namespace isolation is the *PID namespace* [Emelyanov and Kolyshkin(2007)], which grants the ability to create sets of tasks such that each set is completely independent from one another. Thus, two processes belonging to different sets of tasks, can have the exact same ID, without any ambiguity since they do not belong to the same set.

Another interesting contender in the container's scene, is the ever popular Docker. Released on March 2013, this software is only around a year and half old, and it already has its own convention, DockerCon [Hykes(2014)], and is endorsed by major technological companies such as IBM, and RedHat (to name a few). Docker is open-source and provides means to automate deployment of applications within containers. Thus, it provides a higher-level interface to containers, by abstracting the intricacies and specificities into an intuitive and easy to use high-level API. This is the reason that we will use Docker for our virtualization needs in our proof of concept, since it provides a simpler interface, but it should be noted that using LxC would be recommended for a more complete implementation. Because it is not needed to provided this level of abstraction for our Cloud Computing Infrastructure, and it would be beneficial for less powerful machines not having to provide this which would result in a diminution of the overhead.

From a Platform-as-a-Service model point of view, this kind of technology solves a lot of important issues that rises from using a heterogeneous set of resources. As far as we are concerned, from our literary review, we are the first to propose the use of containers (or Light Virtualization), in the context of Cloud Computing, as a mean to provide physical virtualization of the resources. In the following subsection we will present Docker and its characteristics.

6.2. **Docker.**

References

[Babaoglu et al.(2012)Babaoglu, Marzolla, and Tamburini] Babaoglu, Ozalp, Moreno Marzolla, and Michele Tamburini (2012), "Design and implementation of a p2p cloud system." In *Proceedings of the 27th Annual ACM Symposium on Applied Computing*, 412–417, ACM.

[Bandara and Jayasumana(2012)] Bandara, HMN Dilum and Anura P Jayasumana (2012), "Evaluation of p2p resource discovery architectures using real-life multi-attribute resource and query characteristics." In *Consumer Communications and Networking Conference (CCNC), 2012 IEEE*, 634–639, IEEE.

[Bandara and Jayasumana(2013)] Bandara, HMN Dilum and Anura P Jayasumana (2013), "Collaborative applications over peer-to-peer systems–challenges and solutions." *Peer-to-Peer Networking and Applications*, 6, 257–276.

[Cunsolo et al.(2009)Cunsolo, Distefano, Puliafito, and Scarpa] Cunsolo, Vincenzo D, Salvatore Distefano, Antonio Puliafito, and Marco Scarpa (2009), "Cloud@ home: Bridging the gap between volunteer and cloud computing." In *Emerging Intelligent Computing Technology and Applications*, 423–432, Springer.

[Cunsolo et al.(2010a)Cunsolo, Distefano, Puliafito, and Scarpa] Cunsolo, Vincenzo D, Salvatore Distefano, Antonio Puliafito, and Marco Scarpa (2010a), "Open and interoperable clouds: The cloud@ home way." In *Cloud Computing*, 93–111, Springer.

[Cunsolo et al.(2010b)Cunsolo, Distefano, Puliafito, and Scarpa] Cunsolo, Vincenzo D, Salvatore Distefano, Antonio Puliafito, and Marco Scarpa (2010b), "Open and interoperable clouds: The cloud@ home way." In *Cloud Computing*, 93–111, Springer.

[De la Rosa and Baxley(June 2014)] De la Rosa, Jose and Kent Baxley (June 2014), "Lxc containers in ubuntu server 14.04 lts." `http://en.community.dell.com/techcenter/os-applications/w/wiki/6950.lxc-containers-in-ubuntu-server-14-04-lts`. Accessed: 30-12-2014.

[Demers et al.(1987)Demers, Greene, Hauser, Irish, Larson, Shenker, Sturgis, Swinehart, and Terry] Demers, Alan, Dan Greene, Carl Hauser, Wes Irish, John Larson, Scott Shenker, Howard Sturgis, Dan Swinehart, and Doug Terry (1987), "Epidemic algorithms for replicated database maintenance." In *Proceedings of the sixth annual ACM Symposium on Principles of distributed computing*, 1–12, ACM.

[Distefano et al.(2011)Distefano, Fazio, and Puliafito] Distefano, Salvatore, Maria Fazio, and Antonio Puliafito (2011), "The cloud@ home resource management system." In *Utility and Cloud Computing (UCC), 2011 Fourth IEEE International Conference on*, 122–129, IEEE.

[Distefano and Puliafito(2012)] Distefano, Salvatore and Antonio Puliafito (2012), "Cloud@ home: Toward a volunteer cloud." *IT Professional*, 14, 27–31.

[Emelyanov and Kolyshkin(2007)] Emelyanov, Pavel and Kir Kolyshkin (2007), "Pid namespaces in the 2.6. 24 kernel." *LWN. net, November*.

[Ganesan et al.(2004)Ganesan, Yang, and Garcia-Molina] Ganesan, Prasanna, Beverly Yang, and Hector Garcia-Molina (2004), "One torus to rule them all: multi-dimensional queries in p2p systems." In *Proceedings of the 7th International Workshop on the Web and Databases: colocated with ACM SIGMOD/PODS 2004*, 19–24, ACM.

[Ghemawat et al.(2003)Ghemawat, Gobioff, and Leung] Ghemawat, Sanjay, Howard Gobioff, and Shun-Tak Leung (2003), "The google file system." In *ACM SIGOPS Operating Systems Review*, volume 37, 29–43, ACM.

[Hykes(2014)] Hykes, Solomon (2014), "Dockercon." `http://www.dockercon.com/`. Accessed: 2014-12-30.

[Jelasity and Kermarrec(2006)] Jelasity, Mark and A-M Kermarrec (2006), "Ordered slicing of very large-scale overlay networks." In *Peer-to-Peer Computing, 2006. P2P 2006. Sixth IEEE International Conference on*, 117–124, IEEE.

[Jelasity et al.(2009)Jelasity, Montresor, and Babaoglu] Jelasity, Márk, Alberto Montresor, and Ozalp Babaoglu (2009), "T-man: Gossip-based fast overlay topology construction." *Computer networks*, 53, 2321–2339.

[Jelasity et al.(2007)Jelasity, Voulgaris, Guerraoui, Kermarrec, and Van Steen] Jelasity, Márk, Spyros Voulgaris, Rachid Guerraoui, Anne-Marie Kermarrec, and Maarten Van Steen (2007), "Gossip-based peer sampling." *ACM Transactions on Computer Systems (TOCS)*, 25, 8.

[Lewis(2011)] Lewis, Brian (2011), "Separation of responsibilities." Taken from http://mythoughtsonit.com/2011/04/infrastructure-as-a-service-platform-as-a-service-software-as-a-servicetake-a-look-at-the-management-stack, Consulted: November 19th 2014.

[Licklider(1963)] Licklider, Joseph CR (1963), "Memorandum for members and affiliates of the intergalactic computer network." *Apr*, 23, 350–1.

[Lua et al.(2005)Lua, Crowcroft, Pias, Sharma, Lim et al.] Lua, Eng Keong, Jon Crowcroft, Marcelo Pias, Ravi Sharma, Steven Lim, et al. (2005), "A survey and comparison of peer-to-peer overlay network schemes." *IEEE Communications Surveys and Tutorials*, 7, 72–93.

[Maymounkov and Mazieres(2002)] Maymounkov, Petar and David Mazieres (2002), "Kademlia: A peer-to-peer information system based on the xor metric." In *Peer-to-Peer Systems*, 53–65, Springer.

[Mell and Grance(2011)] Mell, Peter and Tim Grance (2011), "The nist definition of cloud computing." x.

[Menage(2011)] Menage, Paul (2011), "Linux kernel documentation/cgroups/cgroups. txt."

[O'reilly(2007)] O'reilly, Tim (2007), "What is web 2.0: Design patterns and business models for the next generation of software." *Communications and Strategies*, 65, 17–37.

[Panzieri et al.(2011)Panzieri, Babaoglu, Ferretti, Ghini, and Marzolla] Panzieri, Fabio, Ozalp Babaoglu, Stefano Ferretti, Vittorio Ghini, and Moreno Marzolla (2011), *Distributed computing in the 21st century: Some aspects of cloud computing*. Springer.

[Pasquet et al.(2014)Pasquet, Maia, Rivière, and Schiavoni] Pasquet, Mathieu, Francisco Maia, Etienne Rivière, and Valerio Schiavoni (2014), "Autonomous multi-dimensional slicing for large-scale distributed systems." In *Distributed Applications and Interoperable Systems*, 141–155, Springer.

[Rimal et al.(2009)Rimal, Choi, and Lumb] Rimal, Bhaskar Prasad, Eunmi Choi, and Ian Lumb (2009), "A taxonomy and survey of cloud computing systems." In *INC, IMS and IDC, 2009. NCM'09. Fifth International Joint Conference on*, 44–51, Ieee.

[Riviere and Voulgaris(2011)] Riviere, Etienne and Spyros Voulgaris (2011), "Gossip-based networking for internet-scale distributed systems." In *E-Technologies: Transformation in a Connected World*, 253–284, Springer.

[Vaquero et al.(2008)Vaquero, Rodero-Merino, Caceres, and Lindner] Vaquero, Luis M, Luis Rodero-Merino, Juan Caceres, and Maik Lindner (2008), "A break in the clouds: towards a cloud definition." *ACM SIGCOMM Computer Communication Review*, 39, 50–55.

[Youseff et al.(2008)Youseff, Butrico, and Da Silva] Youseff, Lamia, Maria Butrico, and Dilma Da Silva (2008), "Toward a unified ontology of cloud computing." In *Grid Computing Environments Workshop, 2008. GCE'08*, 1–10, IEEE.

[Zhang et al.(2010)Zhang, Cheng, and Boutaba] Zhang, Qi, Lu Cheng, and Raouf Boutaba (2010), "Cloud computing: state-of-the-art and research challenges." *Journal of internet services and applications*, 1, 7–18.