Francois D'Ugard



MISSION CRITICAL CLOUD COMPUTING

Final Deliverable

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This project will deliver mission assurance to mission-critical applications in cloud computing systems. We will do so by leveraging the unique capabilities that develop a virtual machine based approach to run applications with good security and reliability in typical cloud computing systems. This project will build upon the previous project's results:

1) A VM management system that dynamically migrate VMs across hosts on an OpenStack-based cloud platform;

2) A P2P overlay network that interconnect the OpenStack VMs based on the IP-over-P2P (IPOP) framework. The project will focus on developing an extension to IPOP that will allow for the communications among the VMs to be routed by an overlay network in an OpenStack-based cloud system.

# Executive Summary

Virtualization is an increasingly popular approach to manage rising information technology costs and complexity in every sector of the economy. Cloud computing allows organizations of any size to provision infrastructure resources as needed and flexibly scale technology resources to meet changing demands. Cloud providers pool hardware resources and allocate them based on the requests of their users. In order to efficiently allocate these resources providers must aggregate users of different requirements and workloads onto the same physical infrastructure. However, this approach increases the likelihood that a malicious user can collocate a VM alongside a target VM in order to extract information or disrupt its functioning in some way.

We propose a solution that can deliver mission assurance to mission-critical applications in cloud computing systems. We will do so by leveraging the unique capabilities of virtualization technology that and develop a dynamic and distributed approach to run applications with good security and reliability in typical cloud computing systems.

Our approach relies on developing a complete network graph on virtual private network peer to peer connections. With the purpose of reducing the likelihood of a malicious VM locating the mission-critical VM and achieving co-residency with it.

This project will deliver mission assurance to mission-critical applications in cloud computing systems. We will do so by leveraging the unique capabilities that develop a virtual machine based approach to run applications with good security and reliability in typical cloud computing systems. This project will build upon the previous project's results namely a P2P overlay network that interconnect the OpenStack VMs based on the IP-over-P2P (IPOP) framework. The project will focus on developing an extension to IPOP that will allow for the communications among the VMs to be routed by an overlay network in an OpenStack-based cloud system.

This document is the final deliverable it is a composition of the feasibility and project plan, the requirements document and the design document.

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# Introduction

Virtualization is an increasingly popular approach to manage rising information technology costs and complexity in every sector of the economy. Cloud computing allows organizations of any size to provision infrastructure resources as needed and flexibly scale technology resources to meet changing demands. Cloud providers like Amazon, Microsoft, or Rackspace pool hardware resources such as compute, memory, and storage and allocate them based on the provisioning requests of their users and available resources. In order to efficiently and cost effectively allocate these resources providers must necessarily aggregate users of different requirements and workloads onto the same physical infrastructure.

The rising popularity and diffusion of hardware virtualization technology among organizations of every size has led researchers and technology professionals to seriously consider the security of such computer systems. By allocating the virtual machines of different user onto the same infrastructure various security vulnerabilities are created. However many of the unique capabilities of cloud computing can also be used to increase the reliability of the cloud as well as ensure its security and resilience to an attack.

An important quality of virtualization is the ability for users to quickly provision resources as needed. This capability lends itself well to the concept of migration wherein a virtual machine is suspended or shutdown and its resources are reallocated to another physical machine and then restarted or rebooted. This capability can be used to ensure the security of a cloud computing environment.

## Problem Definition

The rising popularity of cloud computing concepts has introduced significant security vulnerabilities into the information technology infrastructure of many organizations. Currently virtualized information technology systems are designed and built to operate on relatively static configurations. Typically cloud services providers fulfill provisioning requests on an as needed basis. In order for cloud computing to remain cost effective infrastructure providers must provision pools of resources, such as CPU, memory, and storage among many different users.

This configuration means that a malicious user can reside alongside a virtual machine that computes mission critical or sensitive data. The sharing of physical infrastructure among virtual machines belonging to different users opens up the possibility of a side-channel attack. A side channel attack occurs when a malicious users is able to locate a target virtual machine and spawn another virtual machine alongside this target. The malicious user is then able to extract information by monitoring the hardware resources shared by both virtual machines.

## Scope of System

We propose a distributed peer to peer virtual private network that maintains the communication network structure of collaborating virtual machines unchanged allowing a decoupling between networking services within the cloud framework and the communications network used by the virtual machines. In order to increase the resiliency of said network we propose a system that masks the communication between the virtual machines, obfuscating the communication patterns of virtual machines. Our system will be leveraging and extending IP over P2P (IPOP), a virtual network software that allows users to create virtual private networks (VPNs). IPOP will be extended such that it will allow users to join a VPN with the VMs of their. This will entail functionality to join the VPN, leave it, and communicate information correctly between VMs.

Our system should be easy to understand, setup, and use. This will require developing a command-line tool to access the system’s features as well as implementing the service so that it integrates well among existing OpenStack modules.

## Development Methodology

During the development of our system we followed the Unified Software Development Process. This software process model is iterative and use case driven.

In the Requirements Document we defined a set of use cases that capture the functional requirements of the system and define the contents of the iterations. This has helped us during the System and Object Design phases because it has allowed us to easily identify the architectural patterns to be used, facilitated the subsystem decomposition process, and provided a guide for the selection of the design patterns that will be applied during implementation.

The system uses the three-tier and the peer to peer architectural patterns. The reasons for selecting these patterns are the following:

Three-tier: The three-tier architecture pattern partitions an application into three tiers of functionality that may or may not correspond to distinct physical locations. The most relevant feature of this pattern is that it enables flexibility and reusability of the different logical layers of the application. Each layer can evolve independently to incorporate better implementation techniques and algorithms to better fit the evolving system requirements. The two main tools upon which we are building this system as required by our client, OpenStack and IPOP, are built as layered applications to reap the benefits described above.

Peer to Peer: A Peer-to-peer (P2P) network pattern is a distributed software architecture that partitions network workloads between peers. Our system relies on peers making a portion of their network bandwidth, directly available to other authorized network participants. Participants in our VPN network are both suppliers and consumers of network bandwidth. Each member contributes processing power in the form of random path generation or forwarding when required to do so.

## Definitions, Acronyms, and Abbreviations

API - Application Programming Interface: specifies how some software components should interact with each other [16].

Cloud computing: this phrase commonly refers to network-based services, which appear to be provided by real server hardware, and are in fact served up by virtual hardware that is simulated by software running on one or more physical machines [17].

Co-residency: a VM is co-resident with any VM when they are running on the same physical machine, and describes a great security risk when hosting VMs with sensitive data.

IP Address - Internet Protocol address: a numerical label assigned to each device participating in a computer network that uses the Internet Protocol for communication [19].

Hardware virtualization: this term refers to the creation of a virtual machine that acts like a real computer running an operating system [26].

LAN - Local Area Network: a computer network that interconnects computers in a limited area such as a home or a school using network media [21].

P2P network - Peer-to-peer network: a type of decentralized and distributed network architecture in which individual nodes in the network (called "peers") act as both suppliers and consumers of resources [22].

Side-channel attack: any attack based on information gained from the physical implementation of a cryptosystem, rather than brute force or theoretical weaknesses in the algorithms [23].

VM - Virtual Machine: a software-based emulation of a physical computer [27].

VMM - Virtual Machine Monitor or hypervisor: a piece of computer software, firmware, or hardware that creates and runs virtual machines [20].

Virtual network: a computer network that consists of virtual network links as opposed to physical (wired or wireless) links between connected devices. It is implemented using methods of network virtualization [28].

VPN - Virtual Private Network: A VPN extends a private network across a public network, such as the Internet. It enables a computer to send and receive data across shared or public networks as if it were directly connected to the private network, while benefiting from the functionality, security and management policies of the private network [29].

## Overview of Document

This document is organized into various different sections. Chapter 1 is an introductory section. Section 1.1 defines and describes the problem we will solve. 1.2 defines the scope of the system. Section 1.3 explains the overall development methodology of our system. Section 1.4 Defines acronyms, and abbreviations used throughout the document.

Chapter 2 is a study into the feasibility of the proposed system. Section 2.1 describes the current system in place and identifies its current limitations and constraints. Section 2.2 compares other possible solutions and based on this analysis section 2.3 presents our recommended solution.

Chapter 3 is the project plan. The project plan describes the organization of the project in section 3.1 Also included in section 3.1.1 is the project personnel organization and hard ware and software resources in section 3.1.2. Section 3.2 clearly states that tasks, milestones and deliverables expected upon completion of the project. Section 3.3 identifies the costs associated with the project.

Chapter 4 outlines the system requirements. Section 4.1 presents the functional and non-functional requirements of the system. Section 4.2 analysis the requirements of the system.

Chapter 5 discusses the overall system design. Section 5.1 provides an overview of system decomposition to identify the architectural patterns used and state why they were selected. Section 5.2 describes each of the major subsystems identifying the use cases associated with each subsystem. Section 5.3 describes the mapping of subsystems to hardware and software. Section 5.4 identifies data that needs to be stored. Section 5.5 address the security and privacy concerns encountered in the system.

Chapter 6 is the Detailed Design chapter. Section 6.1 briefly describes the behavior and structure of each subsystem. Section 6.2 is the static model it provides a detailed description of the structure for each subsystem. Section 6.3 Introduces the dynamic models used within the. Section 6.4 is the code specification it describes the class interfaces.

Chapter 7 System Validation. Section 7.1 describes the subsystem tests. Section 7.2 describes the system wide tests. Section 7.3 evaluates our testing methodology indicating if the tests were successful.

Chapter 8 is the document global glossary. This chapter defines terms used in document, especially domain specific terms.

Chapter 9 is the Appendix. This chapter includes all ancillary documentation from previous chapters the helps to describe or specify particular details of the project

Finally Chapter 10 is a bibliographic reference of any works cited in this document.

# Feasibility Study

The following section analyzes the current system and compares the feasibility of our proposed system considering the current system as well as other alternative solutions. Section 2.1 is a description of the current system, afterward section 2.2 provides an overview of the proposed system. Section 2.3 outlines the user’s requirements of a new system. Section 2.4 outlines alternative solutions to the problem. Section 2.5 finalizes our recommendations for a new system based on the information gathered in the previous sections.

## 2.1. Description of Current System

Currently virtualized information technology systems are designed and built to operate on static configurations. Typically cloud services providers fulfill provisioning requests as requested by their user base. In order for cloud computing to remain cost effective infrastructure providers must provision pools of resources, such as CPU, memory, and storage among many different users. This policy, while cost effective and efficient, opens up the cloud to the possibility of a side channel attack. By mapping the internal structure of the cloud environment a malicious attacker is able to identify a target virtual machine a spawn a malicious virtual machine co-resident to the target. This allows the malicious virtual machine to monitor the shared physical infrastructure and extract sensitive or mission critical data.

Distributed applications require a solution that will guarantee reliable and resilient communication. The current IPOP architecture address this by creating a virtual private network over a peer to peer overlay that allows the virtual machine to communicate using static virtual IP addresses. These ip address should remain constant even when changes in the cloud network, like frequent migrations or failures, take place. However the standard IPOP controllers are not designed to masquerade network traffic among cooperative virtual machines. In particular, current controllers manage link creation and termination in a reactive fashion and do not offer solutions to randomly route packets among the cooperating virtual machines. On the contrary current IPOP controllers are designed with efficiency in mind, creating links of shortest path with no consideration to network latencies and masquerading.

## Alternative Solutions

This section provides an overview of existing alternative solutions for the components of our project. The goal of this project is to protect Mission critical virtual machines processing confidential or sensitive data. Approaches that limit the attacker’s ability to successful place a malicious virtual machine co-resident with their target virtual machine or monitor network traffic between co-resident virtual machines will be considered. A brief description of the project problems and background information are included bellow.

1. Communication Network
   1. Centralized host communication server
   2. VPN P2P Overlay Network (IPOP)

### Description of Alternatives

This section provides a high level description of the proposed alternative solutions

Communication Network

1. Centralized host communication server

A predetermined and centralized host list server is known to all virtual machines. Communications flow from the host list server to all other virtual machines within the cloud.

1. VPN P2P Overlay Network

Network information is distributed across the network instead of a central host list server. Communications between virtual machines are routed over a private P2P virtual network. Upon migration link reestablishment with highly collaborative virtual machines takes precedence over other virtual machines.

### Selection Criteria

We consider three criteria for the selection of project solutions they are

* Operational Feasibility
  + This criteria measures the benefit that a solution will have on the daily operations of a cloud administrator. It also measures the effectiveness of a solution and the likelihood of the solution being used effectively.
* Technical Feasibility
  + This criteria describes the maturity of the technology that a proposed solution depends on. It also measures the capability of the team members and the mentor to implement the solution as well as the technology’s effectiveness at solving the problem.
* Economic Feasibility
  + This criteria measures the cost of implementing the solution.

### Analysis of Alternatives

1. Centralized Host Communication Server
   * A centralized communication server introduces a significant, albeit subtle, weakness into a cooperative cloud environment. Once an attacker is co-resident in our cloud, it has the ability to surreptitiously monitor network traffic. Doing so allows the attacker to trivially identify the mission critical virtual machine that resides within our cloud. The mission critical virtual machine is the node that receives the most input and sends the most output traffic. Because this virtual machine is orchestrating the computation functions of all other virtual machines. **Alternatively one can calculate the ratio of incoming to outgoing packets at each node. The closer this ratio is to 1, the higher the likely hood that this virtual machine is the mission critical virtual machine**.
2. VPN P2P Overlay Network
   * A VPN P2P Overlay Network provides similar functionality as the Centralized Host Server without any of the weaknesses. If an attacker is co-resident in our cloud and monitors the network traffic, they will find that it impossible to positively identify the mission critical virtual machine. **Because the network traffic is distributed among all of the friendly nodes in the cloud, each node seems to be sending and receiving approximately the same ratio of communications.** The only alternative is for the attacker is to attempt a system wide parallel attack, iteratively attack each node, or proceed to another attack vector. This increases the likelihood of identifying the attacker virtual machine early and allows the friendly virtual machines time to migrate away from the malicious virtual machine. **Because the system randomly chooses a new path at a certain time interval the average path decay time, path topology, and hop count can be randomized or altered as needed.** This introduces the possibility of implementing honey pot virtual machine or active defense systems. These implementations, however, are left for future work.

## Recommendations

Based on the quantitative study outlined in the previous sections it is the recommendation of this document to proceed with design and implementation of a random and automatic VPN overlay communication network. This approach will best guarantee the security and resilience of a mission critical cloud computing system. The use of a VPN overlay communication network system will reduce the likelihood that a malicious cloud user will be able to accurately identify a mission critical virtual machine. Additionally the system allow any state changed virtual machines to preserve communication and collaboration among their cooperating neighbor nodes.

# Project Plan

This chapter presents the project organization including the personnel assigned to the project, and the mentor and client. We also specify the hardware and software resources required to complete the project. Lastly we identify the tasks, milestones and deliverables of our project and include a timeline of their completion dates.

## 3.1. Project Organization

This section describes the organization of all interested parties participating in the project. This section defines the roles and work domains of all interested parties in order to facilitate effective communication among the team members and the client. Also included in this section is a description of the hardware and software resources required for the successful completion of the project.

## 3.1.1. Project Personnel Organization

|  |  |
| --- | --- |
| **Team member** | **Main work domain** |
| Francois D’Ugard | Migration Management, Communications Network |
| Dr. Ming Zhao | Mentor, Client and Guidance |

Figure 3.1.1 - Team Member Work Domains

|  |  |
| --- | --- |
| **Team member** | **Role** |
| Francois D’Ugard: | Lead Developer, Tester, Project Manager |
| Dr. Ming Zhao | Mentor, client |

Figure 3.1.2 - Team Member Roles

## 3.1.2. Hardware and Software Resources

The following section lists the hardware and software resources necessary for the successful completion of the project.

* Hardware
  + 1 personal computer for development, testing, and demos. Minimum requirements: Dual-core CPU @ 1.2 GHz, 2GB RAM, 128GB HDD.
  + 2+ servers where the cloud infrastructure will be set up. Minimum requirements: Dual-core CPU @ 1.4 GHz, 8GB RAM, 500 GB HDD, 2 x 1Gbps PCI LAN interfaces.
* Software
  + OpenStack cloud computing platform.
  + IPOP Peer to peer VPN networking controller
  + Graphtool Python library for efficient network analysis
  + Python 2.7
  + Ubuntu Server 12.04 or 14.04 LTS.
  + Google Drive, Google Talk, and Gmail for collaboration.
  + Microsoft Word, Microsoft Excel, Microsoft PowerPoint, and Adobe Reader
  + StarUML - UML modeling tool.
  + Unittest - a unit test framework for Python.
  + Pencil for user interface mockups.

## 3.2. Identification of Tasks, Milestones, and Deliverables

All tasks are identified with a unique string in the format of component number, milestone number, and task number i.e. C#M#T#.

* Setup Development Environment
  + Milestone 1: Complete setup of development environment and network configuration and setup NFS file system to support live migration capabilities of OpenStack.
    - C1M1T1: Install Hardware Components
    - C1M1T2: Install Ubuntu 12.04 on all development machines
    - C1M1T3: Configure Development Network
    - C1M1T4: Deploy OpenStack cloud to all development machines
    - C1M1T5: Setup Network File sharing service for live migration
* Communications Network: Design and implementation of a distributed P2P VPN communications network that obfuscates communications with collaborating virtual machines and prioritizes communication reestablishment by communication history.
  + Milestone 2: Design distributed collaborative communication network using IPOP P2P VPN.
    - C3M2T1: Design modifications to IPOP controller
    - C3M2T2: Design link restoration algorithm based on communications history
    - C3M2T3: Design communications obfuscation algorithm to hide mission critical communications between collaborating virtual machines.
  + Milestone 3: Implement Communications Network Component
    - C3M3T1: Implement Communications Network link reestablishment Algorithm
    - C3M3T2: Implement Communications Network obfuscation Algorithm
    - C3M3T3: Implement Command line interface for Communications Network component
  + Milestone 4: Integrate Communications Network Component into OpenStack system
    - C3M4T1: Systems integration and testing.

### 3.2.1 Project Milestones

1. Complete setup of development environment and network configuration and setup NFS file system to support live migration capabilities of OpenStack.
2. Communication network using IPOP P2P VPN Design complete
3. Implement Communications Network Component
4. Create Unit Tests for Communications Systems
5. Integrate Communications Network Component into OpenStack system

### 3.2.2. Deliverable Timeline:

9/8/2014

Feasibility Study and Project Plan. First draft.

Requirements Document. First draft.

Feasibility Study and Project Plan. In-class presentation.

9/15/2014

Feasibility Study and Project Plan. Second draft.

9/22/2014

Feasibility Study and Project Plan. Final draft.

Feasibility Study and Project Plan. In-class presentation

9/29/2014

Requirements Document. Second draft.

Requirements Analysis.

10/6/2014

Requirements Document. Final draft.

Requirements Analysis. In-class presentation.

Design Document. First draft.

10/20/2014

Design Document. Second draft.

System and Detailed Design. In-class presentation.

10/27/2014

Design Document. Final draft.

System and Detailed Design.

Implementation and Unit Testing. First code review.

11/17/2014

Implementation and Unit Testing. Second code review.

In-class presentation.

11/24/2014

Implementation and Unit Testing. Final code.

Implementation and Unit Testing.

Integration and System Testing. First code review.

## 3.3 Cost Estimate

|  |  |  |
| --- | --- | --- |
| **Resource** | **Quantity** | **Cost** |
| Server | 2 | $5,000 |
| Personal Computer | 1 | $1,400 |
| Software | Open Source | $0 |
| Personnel (Hours @ $40) | 480 | $19,200 |
| **TOTAL** |  | **$30,600** |

Figure 3.3 - Cost Estimate Breakdown

# System Requirements

This chapter covers the requirements of the proposed system. We start by presenting a high-level description of the system in the form of functional and nonfunctional requirements in section 4.1. In section 4.2 we delve into the details of the system requirements by developing the analysis models, which define the complete functional specification of the system. In particular, in this section we describe the diagrams in the Appendices B, C, and D and validate the models against the uses cases listed in Appendix A.

## 4.1. Functional Requirements and Non-functional Requirements

In this section we present a high-level description of the functionality of the system in terms of functional requirements and the associated non-functional requirements for usability, reliability, performance, and/or supportability.

## 4.1.2 MC2 Controller

* The system shall allow the user to configure a VPN to interconnect a group of collaborating virtual machines while masquerading their network traffic.
  + Usability:
    - The VPN shall support the execution of unmodified applications that use the standard TCP and UDP protocols.
    - The VPN shall not impose significant constraints in the network infrastructure required for operation. In particular, the VPN shall allow communication through firewalls and NATs.
    - Initialization of the VPN shall be accessible from a command line interface useable by a computer savvy use.
    - A short description of each option executable in the system help.
    - The system shall automatically download all required files to install and run the VPN service.
  + Performance:
    - The system shall finish the setup in less than one minute after the user issues a complete and correct command on a 100 Mbps network with Internet access.
  + Supportability:
    - This feature shall function correctly in all POSIX-compliant OS.
* The system shall allow the user to join the VPN based on the configuration file previously created.
  + **Usability:** 
    - This feature shall be accessible from a command line interface simple enough for a computer savvy user to use without training.
    - A short description of each option executable in the system help.
  + **Performance:** 
    - The system shall join the VPN in less than 30 seconds after the user invokes the command with a correct configuration file on a 100 Mbps network where the XMPP server is reachable.
  + **Supportability:** 
    - This feature shall function correctly in all POSIX-compliant OS.
* The system shall allow the user to leave the VPN at any time.
  + **Usability:** 
    - This feature shall be accessible from a command line interface simple enough for a computer savvy user to use without training.
  + **Performance:** 
    - The system shall disconnect from the VPN and remove the network interface in less than ten seconds after the user invokes the command.
  + **Supportability:** 
    - This feature shall function correctly in all POSIX-compliant OS.
* The system shall allow the user to set up an open-source XMPP server for the collaborating VMs to discover each other and join the VPN.
  + **Usability:**
    - This feature shall be accessible from a command line interface simple enough for a computer savvy user to use without training.
  + **Performance:** 
    - **T**he system shall finish the setup in less than one minute after the user issues a complete and correct command on a 100 Mbps network with Internet access.
  + **Supportability:** 
    - This feature shall function correctly in all POSIX-compliant OS.

## 4.2. Analysis of System Requirements

This section contains the complete functional specification that will guide designers and programmers during the realization of the system. In particular, this section presents the elicited scenarios and describes the diagrams in the Appendices B, C, and D.

### 4.2.1. Scenarios

The following are the scenarios elicited during our interviews with the client as part of the requirements elicitation phase.

### VPN over P2P

Allow VM to communicate in dynamic cloud environment.

John wishes to deploy a Hadoop cluster across two public clouds with 100 VMs he has created in order to run a distributed hurricane simulation software.

For simplicity, John named his VM “vm-1”, “vm-2”, and so on, up to 100.

Since he will be dealing with sensitive insurance data, he decides to activate the MC2 service to improve the cluster’s resiliency. In order to create this VPN, John creates an additional VM and calls it “xmpp” and installs an XMPP server on it. Then John configures his 100 VMs to use the XMPP server. When John receives confirmation that all VMs are ready to connect to the network, he joins all VMs to the network and receives confirmation from all of them.

Disconnect VM from VPN. John’s VMs are working as expected, but he wants to make sure they can reach each other over the VPN. He logs in to vm-1 and pings the virtual IP of vm-10 to vm-15. Then John decides to remove vm-10 from the VPN and ping it again. When John realizes the VM is unreachable, he adds the VM back to the VPN.

### 4.2.2. Use Case Model

The functional model of the proposed system is captured by the use case diagram found in Appendix B. Created with the standard notation of the Unified Modeling Language (UML), this diagram describes the functionality of the proposed system from the user’s perspective.

The system we are proposing will allow cloud administrators to have access to the list of instances for which the service is enabled. The uses case that provide this functionality are start, stop, restart, join and leave.

In order to maintain the communication among the migrated VM and its collaborating peers outside the cloud, the administrator will be able to set up an XMPP server, configure the VMs to use the server. In addition, the administrator will also be able to remove nodes from the virtual network.

### 4.2.3. Static Model

The static model of the system is captured by the class diagrams in Appendix C. The vpn communication system makes use of the IPOP and MCVPN command line Interface to be able to prepare the XMPP Server that will be responsible for initial discovery and status updates among the cooperating VMs.

### 4.2.4. Dynamic Model

The dynamic model of the system is captured by the sequence diagrams in Appendix D.

First, cloud users may install or stop the XMPP server. The installation configures the XMPP server that will bootstrap the VPN network, which is used for initialize communication among the virtual machines. A user may then joins the VMs that will be nodes on the P2P network. Lastly, a user may leave the P2P network. In addition, administrators may, at any given time start, stop, restart the service.

1. System Design

In this chapter we give an overview of the system by presenting a package diagram of its major subsystems, identifying the architectural patterns used in the system and justifying their selection in section 2.1. In section 2.2, we describe the major subsystems in detail and identify the requirements associated with each subsystem. We present the hardware and software mapping for the system, including a deployment diagram, in section 2.3. In section 2.4, we describe the persistent data managed by the system.

## Overview

As shown in the figure, the architectural patterns of the system are the three-tier and the peer to peer pattern. The reasons for selecting these patterns are the following:

Three-tier: The three-tier architecture pattern partitions an application into three tiers of functionality that may or may not correspond to distinct physical locations. The most relevant feature of this pattern is that it enables flexibility and reusability of the different logical layers of the application. Each layer can evolve independently to incorporate better implementation techniques and algorithms to better fit the evolving system requirements. The two main tools upon which we are building this system as required by our client, OpenStack and IPOP, are built as layered applications to reap the benefits described above.

Peer to Peer: A Peer-to-peer (P2P) network pattern is a distributed software architecture that partitions network workloads between peers. Our system relies on peers making a portion of their network bandwidth, directly available to other authorized network participants. Participants in our VPN network are both suppliers and consumers of network bandwidth. Each member contributes processing power in the form of random path generation or forwarding when required to do so.

## Subsystem Decomposition

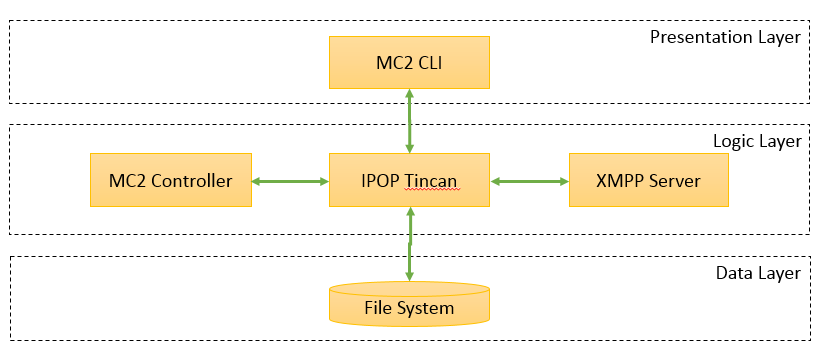


Figure 5.2. – Three Tier Architecture

VPN over P2P

MCVPN Interface: Successfully operating a VPN using IPOP requires the user to download, install, and configure several pieces of software. The current IPOP project provides adequate documentation on how to achieve this, but there is no centralized tool that automatically carries out the steps and provides access to all the features. This command-line interface will hide most of the technical details of the process from the user.

MC2 VPN Controller: The proposed system will be employed in an environment where a group of VMs running a distributed application and actively exchanging data in order to solve a problem.

TinCan: “In IPOP, TinCan links are bi-directional communication channels that connect user devices end-to-end to other trusted user devices. … IPOP TinCan links carry tunneled IP packets (IPv4 or IPv6). Packets are intercepted by virtual network interfaces (tap) and then tunneled by IPOP through TinCan links; at the destination, they are injected again into a virtual network interface. This allows existing IPv4 (or IPv6) applications to work unmodified when running over an IPOP virtual network. IPOP’s implementation of TinCan links leverages extensively the libjingle open-source code, which is widely used and can run on a variety of platforms. The IPOP-TinCan module in the source code is primarily responsible for the creation, management, and tear-down of individual TinCan links with peers. This is done under coordination of IPOP’s controller module; controller and TinCan are decoupled modules that communicate through an API layered upon local host sockets, allowing flexibility in the design and facilitating the development of new IPOP-based VPNs.” [2]

## Hardware and Software Mapping

In this section we map the subsystems to hardware and software resources. Figure 2 shows a descriptive deployment diagram that displays the associations between the subsystems and the hardware. The separation among layers of the three-tier architecture is applied to the software components rather than with the physical hardware. In the deployment diagram below, the physical controller node (MC2 Host) hosts components of all three layers: the Dashboard and the Apache web server fall within the interface layer, the MySQL DBMS and the ext4 file system are part of the data layer, while all other components are part of the logic layer. MC2 and Visa Lab are physical compute nodes with the same components, but hosting several VMs with different functions. On these physical nodes, the ext4 file system is part of the data layer while all other components are part of the logic layer. All virtual devices host component of all three layers. The MCVPN and MC2 Controller applications are part of the interface layer, the ext4 file system being part of the data layer, and all other components are part of the logic layer. Finally, the virtual machine devices in the diagram contains the actual MC2 Controller instance for that particular virtual machine.

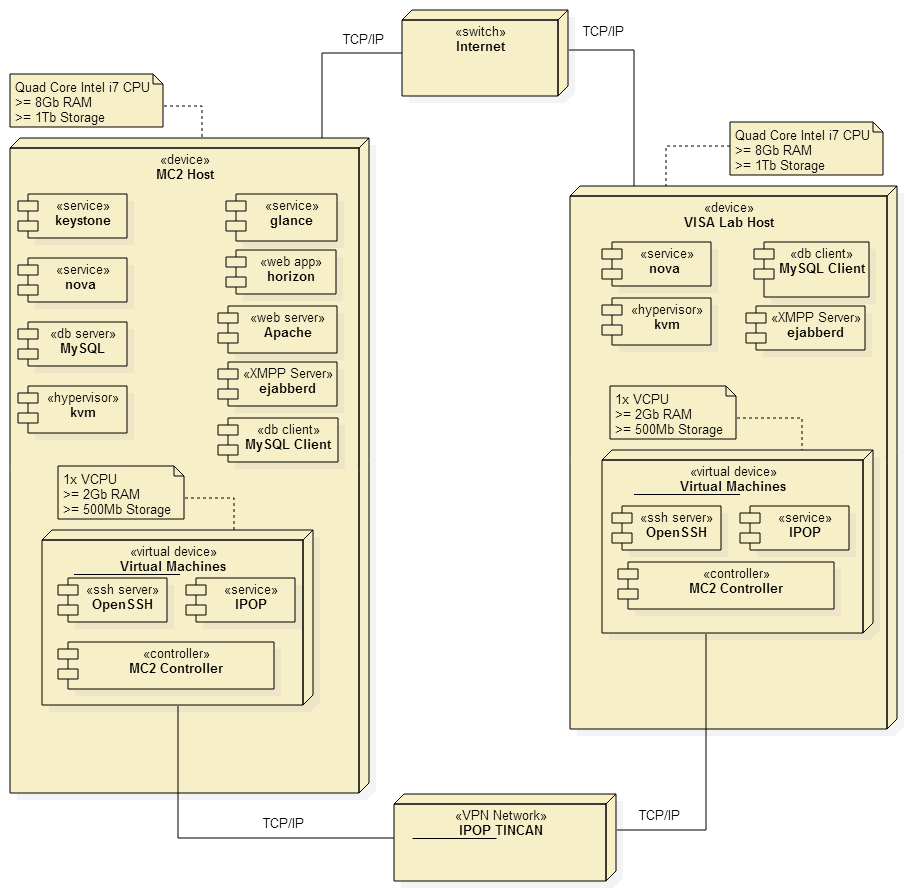


Figure 5.3. - Hardware Software Mapping

## 5.4. Persistent Data Management

The storage and management of persistent data is critical to the operation of the software components. Below is a data dictionary that describes the most pertinent data variables used within our system.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Entity** | **Attribute** | **Data Type** | **Description** | **Possible Values** | **Constraints** |
| Instance | Max\_Latency | Int | Maximum allowable latency over entire path. | Nonnegative Integers. | Defaults to 1. |
| Instance | Min\_Latency | Int | Minimum allowable latency over entire path. | Nonnegative Integers. | Defaults to 0. |
| Instance | Hop\_Count | Int | Total number of required hops within path | Nonnegative Integers. | Defaults to 1. |
| Instance | Path\_Decay | Int | Amount of time in seconds before path needs to be recalculated. | Nonnegative Integers. | Defaults to 30. |

Figure 5.4. - Data Dictionary

## 5.5. Security and Privacy

Fortunately many of the user authentication functions belong to system components outside of the scope of this project. For example IPOP-Tincan relies on a security key generated by the XMPP server that allows it to authenticate with and connect to nodes within its group that request tincan links.

Since tincan connections rely on ad hoc creation and re-creation of the network topology, all such data is stored temporarily in memory and pulled from memory. This is an advantage of the system in that it allows for automatic discovery of the nodes graph/network neighborhood.

Depending on the chosen virtualization implementation the system may rely on an authentication subsystem that manages state changes within the cloud environment. For example, OpenStack uses an authentication subsystem named Keystone that allows administrator level users to apply a set of administrative functions to her cloud group. Similarly Amazon AWS relies on their own proprietary authentication system to allow users to administrate their own public clouds. The design and implementation of such systems is beyond the scope of this project. Work involving identifying and addressing any security loopholes present in our system, is left for future work.

# Detailed Design

We start this chapter by briefly describing the structure of each subsystem in section 3.1. In section 3. 2 we provide a detailed description of the structure of each subsystem by presenting the minimal and detailed class diagrams and the four design patterns we are using. We show the object interactions with the refined sequence diagrams in section 3.3 and describe the class interfaces and constraints for the main control object in each subsystem in section 3.4.

## Overview

In this section we give an overview of the final system MC^2. The MC^2 P2P Masquerading System is comprised of the OpenStack API, the local file and memory system, the MCVPN interface, the MC^2 Controller, and IPOP-TinCan.

## Static model

Both components of the system are shown through the class diagrams (Figure 4 and Figure 5). Mission Critical VPN interface allows the user to set up a Cloud VPN to support network masquerading. The Mission Critical VPN interface, which is exposed to users through a command-line tool, allows users to install and run the XMPP server as well as enable or disable this service.

Activating and deactivating the service for a given virtual machine involves an SSH call into the target virtual machine. For the sake of usability the MCVPN subsystem wraps this functionality. This interface communicates with the MC^2 Controller located at each virtual machine. The MC^2 controller uses the bi-directional TinCan links to establish the private communication between VMs on the VPN. The controller also calculates a new routing path considering latency, and hop requirements and receives and routes packets along this path

The design patterns we will use are the facade and the singleton patterns.

As shown in Figure 4, the MC^2 Controller, XMPP Server, and Path classes use the facade design pattern. These classes provide the caller a high-level interface for creating, deleting, manipulating data relating to each class’ object type. This design pattern reduces the coupling between the classes that contain information about important objects within our system namely Virtual Machine and IPOP-Tincan. The Path class is called upon by the MC^2 Controller Singleton, Path acts as both a façade and lower-level class. By using a facade class, modifications made to those lower-level classes remain transparent to the higher-level classes, a decoupling that is essential for developing an extensible and maintainable system.

The singleton design pattern is realized by the XMPP Server class as Figure 4 shows. This design pattern is required since exactly one object of each of those classes is needed to coordinate the actions across the system.

## Code Specification

**MC^2 Controller:**

***trackTraffic()*** - The trackTraffic function monitors the network traffic of the VM with all its peers and regularly records this activity to form a traffic history log that can be used by the prioritization algorithm. This function is running whenever the VPN is running. This function also updates the internal connection graph edge latency property map.

***createConnection(priority\_list)*** - The createConnection functions receives a peer to which a connection is to be established and it creates the links to that peer.

***get\_ip\_address(ifname)*** - Returns the ip address of the given interface name ifname.

***build\_connection\_graph(fname)*** - Builds a complete connection graph in memory. The function gathers the information of all required nodes from the virtual machines connection graph variable. The function saves an image of the graph with the name fname. Uses the connection table to name each vertex and assigns an ip to each vertex. The vm network is treated as a complete graph. The function draws a graph an outputs it as a file with the given fname file name.

***calc\_latency()*** - Calculates the latencies of the edges between the paths by observing network traffic. Updates graph edge details in con\_graph

***find\_path(min, max, dest***) - Generates a new random path from the source to the destination vm within the required latency bounds min, max. The source is always the controller’s native ip address.

# System Validation

The functions of the system were unit tested using *unittest,* the Python unit testing framework, and Mock, a Python mocking and testing library.

During system testing, we verified the functionality of our systems components including the random path generator.

In particular, our system testing included the following:

* Usability testing of the command line tools that provide Compatibility testing of IPOP Tincan and the MC2 Controller.
* Functionality testing of the random path generating algorithms.

# Glossary

API - Application Programming Interface: specifies how some software components should interact with each other [16].

Cloud computing: this phrase commonly refers to network-based services, which appear to be provided by real server hardware, and are in fact served up by virtual hardware that is simulated by software running on one or more physical machines [17].

Co-residency: a VM is co-resident with any VM when they are running on the same physical machine, and describes a great security risk when hosting VMs with sensitive data.

IP Address - Internet Protocol address: a numerical label assigned to each device participating in a computer network that uses the Internet Protocol for communication [19].

Hardware virtualization: this term refers to the creation of a virtual machine that acts like a real computer running an operating system [26].

LAN - Local Area Network: a computer network that interconnects computers in a limited area such as a home or a school using network media [21].

Live virtual machine migration: the process of moving a running virtual machine from a physical host to another physical host [6].

MTD - Moving-Target Defense: an approach that has been proposed to better protect important network systems and critical computing infrastructure by dynamically changing properties of their configuration in some way [1].

Non-live virtual machine migration: the process of moving a powered off virtual machine from a physical host to another physical host. After the transfer completes, the migrated virtual machine is restarted [6].

P2P network - Peer-to-peer network: a type of decentralized and distributed network architecture in which individual nodes in the network (called "peers") act as both suppliers and consumers of resources [22].

Private cloud: it is a cloud infrastructure operated solely for a single organization. It can be managed internally or by a third-party, and hosted internally or externally [17].

Public cloud: a cloud is said to be public when the services are rendered over a network that is open for public use, most commonly the Internet [17].

Side-channel attack: any attack based on information gained from the physical implementation of a cryptosystem, rather than brute force or theoretical weaknesses in the algorithms [23].

UML - Unified Modeling language: a standardized, general-purpose modeling language in the field of software engineering. It includes a set of graphic notation techniques to create visual models of object-oriented software-intensive systems [25].

Virtual cluster: a group of VMs configured for a common purpose with associated storage resource, operating system, software environment, communication protocol, and network configuration [12].

VM - Virtual Machine: a software-based emulation of a physical computer [27].

VMM - Virtual Machine Monitor or hypervisor: a piece of computer software, firmware, or hardware that creates and runs virtual machines [20].

Virtual network: a computer network that consists of virtual network links as opposed to physical (wired or wireless) links between connected devices. It is implemented using methods of network virtualization [28].

VPN - Virtual Private Network: A VPN extends a private network across a public network, such as the Internet. It enables a computer to send and receive data across shared or public networks as if it were directly connected to the private network, while benefiting from the functionality, security and management policies of the private network [29].

# Appendix

## Appendix A - Project schedule

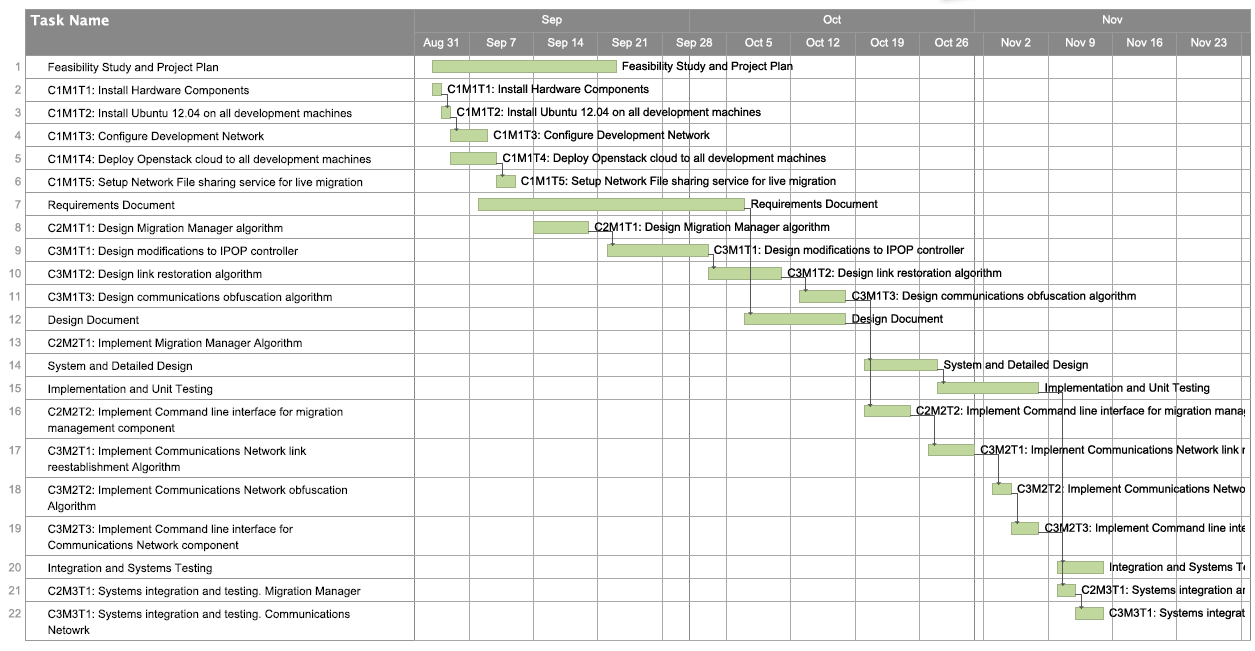


Figure 9.1 - Project Gantt chart

## Appendix B – All use cases with nonfunctional requirements.

### **Use Case – Configure XMPP Server.**

Details:

* Actor: Administrator
* Preconditions:
  + A dedicated XMPP server with access to the internet. A host or virtual machine.
  + The actor is logged into the XMPP server and has super user level privileges on that account.
* Description:
  + The use case begins when the actor runs the xmpp\_setup.py script on the command line of the dedicated XMPP server.
    - The actor must specify the username and password of the first admin user to be created by the script.
      * --user <user name>
      * --password <password>
    - The system will download and install the appropriate packages and then alter the configuration files required to successfully install the XMPP server.
    - The system shall create the admin user with the specified username and password.
    - The use case ends when the system returns a successful message for all requirements.
* Post Conditions:
  + The XMPP Server is setup and running.
  + The Administrator User is created on the XMPP Server.
  + The system returns a success message.

Alternative Courses of Action:

* None.

Exceptions:

* The system fails to download the required packages.
* The system does not recognize the arguments passed by the user.
* The system fails to properly install the packages required.

Related Use Cases:

* Configure VPN.

Decision Support

Criticality: High. This service is critical for the execution and implementation of the system. Without this service the VPN network is not feasible.

Risk: Low. The required packages are open-source and easily downloaded and installed. Documentation and configuration examples are readily available.

Constraints:

* Usability
  + The system shall provide a help menu for each available option that includes a description and example.
* Performance
  + The system shall complete the setup in less than one minute. Not including the time it takes to download the required packages as this is highly variable.
* Supportability
  + Any POSIX-compliant OS will be able to support this function.
* Implementation
  + This functionality will be implemented in its own setup script which will run in the command line. It will be written in Python. This functionality maybe called up by other functions.

Owner: Francois D’Ugard

Initiation date: 10/13/2014

Date last modified: 10/13/2014

### **Use Case – Configure VPN Node.**

Details:

* Actor: Administrator
* Preconditions:
  + A dedicated XMPP server with access to the internet. A host or virtual machine.
  + The XMPP server is running successfully
  + The actor is logged into the VM to be configured as the node.
  + The VPN node is accessible to the XMPP server vice versa.
* Description:
  + The use case begins when the actor runs the vpn\_node\_setup.py script on the command line of the VM.
    - The actor must specify the username and password of the user to be created by the script.
      * --xmpp-user <user name>
      * --xmpp-password <password>
    - The actor must specify the address of the VPN node, the network mask, the IP address of the XMPP server.
      * --ipop-address <ip address assigned to this VM on the VPN>
      * --ipop-mask <network mask>
      * --xmpp-host <IP address of the XMPP server>
    - The system will download and install IPOP then create the configuration file with the given arguments.
    - The system shall create the XMPP user with the specified username and password, via RPC call to the XMPP server.
    - The use case ends when the system returns a successful message for all requirements.
* Post Conditions:
  + The required configuration files have been created on the VM.
  + The User is created on the XMPP Server.
  + The system returns a success message.

Alternative Courses of Action:

* None.

Exceptions:

* The system fails to download the required packages.
* The system does not recognize the arguments passed by the user.
* The system fails to properly install the packages required.
* The system fails to write the configuration file.

Related Use Cases:

* Setup XMPP server.
* Join VPN
* Leave VPN

Decision Support

Criticality: High. This service is critical for the execution and implementation of the system. Without this service the VPN network is not feasible.

Risk: Low. The required packages are open-source and easily downloaded and installed. Documentation and configuration examples are readily available.

Constraints:

* Usability
  + The system shall provide a help menu for each available option that includes a description and example.
* Performance
  + The system shall complete the setup in less than one minute. Not including the time it takes to download the required packages as this is highly variable.
* Supportability
  + Any POSIX-compliant OS will be able to support this function.
* Implementation
  + This functionality will be implemented in its own setup script which will run in the command line. It will be written in Python. This functionality maybe called up by other functions.

Owner: Francois D’Ugard

Initiation date: 10/13/2014

Date last modified: 10/13/2014

### **Use Case – Join VPN.**

Details:

* Actor: Administrator
* Preconditions:
  + A dedicated XMPP server with access to the internet. A host or virtual machine.
  + The XMPP server is running successfully
  + The actor is logged into the VM to be joined into the VPN.
  + The VPN node is accessible to the XMPP server vice versa.
  + There is a correct configuration file available to the function.
* Description:
  + The use case begins when the actor runs the join\_vpn.py script on the command line of the VM.
    - The actor must specify the configuration file.
      * --conf <configuration file>
    - The system will start the ipop-tincan program with the MCCVPN controller.
    - The use case ends when the system returns a successful message for all requirements.
* Post Conditions:
  + There exists a new network interface with the IP and Mask specified in the configuration file.
  + The VM can reach other VMs through the VPN
  + The system returns a success message.

Alternative Courses of Action:

* None.

Exceptions:

* The system does not recognize the arguments passed by the user.
* The system is unable to read or find the specified configuration file.
* The system fails to start the ipop-tincan or MCCVPN controller.

Related Use Cases:

* Setup XMPP server.
* Leave VPN

Decision Support

Criticality: High. This service is critical for the execution and implementation of the system. Without this service the VPN network is not feasible.

Risk: Low. The required packages are open-source and easily downloaded and installed. Documentation and configuration examples are readily available.

Constraints:

* Usability
  + The system shall provide a help menu for each available option that includes a description and example.
* Performance
  + The system shall complete the setup in less than one minute. Not including the time it takes to download the required packages as this is highly variable.
* Supportability
  + Any POSIX-compliant OS will be able to support this function.
* Implementation
  + This functionality will be implemented in its own setup script which will run in the command line. It will be written in Python. This functionality maybe called up by other functions.

Owner: Francois D’Ugard

Initiation date: 10/13/2014

Date last modified: 10/13/2014

### **Use Case – Leave VPN.**

Details:

* Actor: Administrator
* Preconditions:
  + A dedicated XMPP server with access to the internet. A host or virtual machine.
  + The XMPP server is running successfully
  + The actor is logged into the VM to be removed from the VPN.
  + The VM is actually joined to the VPN
  + The VPN node is accessible to the XMPP server vice versa.
* Description:
  + The use case begins when the actor runs the leave\_vpn.py script on the command line of the VM.
    - The system will stop the ipop-tincan program and the MCCVPN controller.
    - The use case ends when the system returns a successful message for the removal of the VM from the VPN network.
* Post Conditions:
  + The IPOP network interface no longer exists on the system.
  + The VM cannot reach other VMs through the VPN
  + The system returns a success message.

Alternative Courses of Action:

* None.

Exceptions:

* The system does not recognize the arguments passed by the user.
* The system fails to stop the ipop-tincan or MCCVPN controller.

Related Use Cases:

* Setup XMPP server.
* Join VPN

Decision Support

Criticality: High. This service is critical for the execution and implementation of the system. Without this service the VPN network is not feasible.

Risk: Low. The required packages are open-source and easily downloaded and installed. Documentation and configuration examples are readily available.

Constraints:

* Usability
  + The system shall provide a help menu for each available option that includes a description and example.
* Performance
  + The system shall complete the setup in less than one minute. Not including the time it takes to download the required packages as this is highly variable.
* Supportability
  + Any POSIX-compliant OS will be able to support this function.
* Implementation
  + This functionality will be implemented in its own setup script which will run in the command line. It will be written in Python. This functionality maybe called up by other functions.

Owner: Francois D’Ugard

Initiation date: 10/13/2014

Date last modified: 10/13/2014

### **Use Case – Start XMPP Server.**

Details:

* Actor: Administrator
* Preconditions:
  + A dedicated XMPP server with access to the internet. Installed on a host or virtual machine.
  + The actor is logged into the XMPP server and has super user level privileges on that account.
  + A correct and complete configuration file is located on the server that is to function as the XMPP server.
* Description:
  + The use case begins when the actor runs the xmpp\_controller.py script on the command line of the dedicated XMPP server.
    - The actor must specify the usage parameter accepted by the script.
      * --start
    - The system will start the XMPP server following the parameters included within the configuration file.
    - The use case ends when the system returns a successful message for all requirements.
* Post Conditions:
  + The XMPP Server is started.
  + The system returns a success message.

Alternative Courses of Action:

* None.

Exceptions:

* The configuration file either incorrect or incomplete or missing.
* The system does not recognize the arguments passed by the user.

Related Use Cases:

* Configure VPN.

Decision Support

Criticality: High. This service is critical for the execution and implementation of the system. Without this service the VPN network is not feasible.

Risk: Low. The required packages are open-source and easily downloaded and installed. Documentation and configuration examples are readily available.

Constraints:

* Usability
  + The system shall provide a help menu for each available option that includes a description and example.
* Performance
  + The system shall complete the setup in less than one minute. Not including the time it takes to download the required packages as this is highly variable.
* Supportability
  + Any POSIX-compliant OS will be able to support this function.
* Implementation
  + This functionality will be implemented in its own setup script which will run in the command line. It will be written in Python. This functionality maybe called up by other functions.

Owner: Francois D’Ugard

Initiation date: 10/15/2014

Date last modified: 10/15/2014

### **Use Case – Stop XMPP Server.**

Details:

* Actor: Administrator
* Preconditions:
  + A dedicated XMPP server with access to the internet. Installed on a host or virtual machine.
  + The actor is logged into the XMPP server and has super user level privileges on that account.
  + The XMPP Service is running.
* Description:
  + The use case begins when the actor runs the xmpp\_controller.py script on the command line of the dedicated XMPP server.
    - The actor must specify the usage parameter accepted by the script.
      * --stop
    - The system shall store the state of all connections, virtual machines, paths, and VPN groups in storage.
    - The system will stop the XMPP server.
    - The use case ends when the system returns a successful message indicating that the server has been stopped successfully.
* Post Conditions:
  + The state of the objects of the system are written to disk.
  + The XMPP Server is stopped.
  + The system returns a success message.

Alternative Courses of Action:

* None.

Exceptions:

* The XMPP Server is not running.
* The XMPP Server is unable to connect to the database.
* The system does not recognize the arguments passed by the user.

Related Use Cases:

* Configure VPN.

Decision Support

Criticality: High. This service is critical for the execution and implementation of the system. Without this service the VPN network is not feasible.

Risk: Low. The required packages are open-source and easily downloaded and installed. Documentation and configuration examples are readily available.

Constraints:

* Usability
  + The system shall provide a help menu for each available option that includes a description and example.
* Performance
  + The system shall complete the setup in less than one minute. Not including the time it takes to download the required packages as this is highly variable.
* Supportability
  + Any POSIX-compliant OS will be able to support this function.
* Implementation
  + This functionality will be implemented in its own setup script which will run in the command line. It will be written in Python. This functionality maybe called up by other functions.

Owner: Francois D’Ugard

Initiation date: 10/15/2014

Date last modified: 10/15/2014

### **Use Case – Restart XMPP Server.**

Details:

* Actor: Administrator
* Preconditions:
  + A dedicated XMPP server with access to the internet. Installed on a host or virtual machine.
  + The actor is logged into the XMPP server and has super user level privileges on that account.
  + The XMPP Service is running.
* Description:
  + The use case begins when the actor runs the xmpp\_controller.py script on the command line of the dedicated XMPP server.
    - The actor must specify the usage parameter accepted by the script.
      * --restart
    - The system shall store the state of all connections, virtual machines, paths, and VPN groups in storage.
    - The system will stop the XMPP server.
    - The system will start the XMPP server.
    - The use case ends when the system returns a successful message indicating that the server has been stopped successfully.
* Post Conditions:
  + The last state of objects within the system are written to disk.
  + The XMPP Server is started.
  + The system returns a success message.

Alternative Courses of Action:

* None.

Exceptions:

* The XMPP Server is not running.
* The XMPP Server is unable to connect to the database.
* The system does not recognize the arguments passed by the user.

Related Use Cases:

* Configure VPN.

Decision Support

Criticality: High. This service is critical for the execution and implementation of the system. Without this service the VPN network is not feasible.

Risk: Low. The required packages are open-source and easily downloaded and installed. Documentation and configuration examples are readily available.

Constraints:

* Usability
  + The system shall provide a help menu for each available option that includes a description and example.
* Performance
  + The system shall complete the setup in less than one minute. Not including the time it takes to download the required packages as this is highly variable.
* Supportability
  + Any POSIX-compliant OS will be able to support this function.
* Implementation
  + This functionality will be implemented in its own setup script which will run in the command line. It will be written in Python. This functionality maybe called up by other functions.

Owner: Francois D’Ugard

Initiation date: 10/15/2014

Date last modified: 10/15/2014

## Appendix C – User Interface designs.

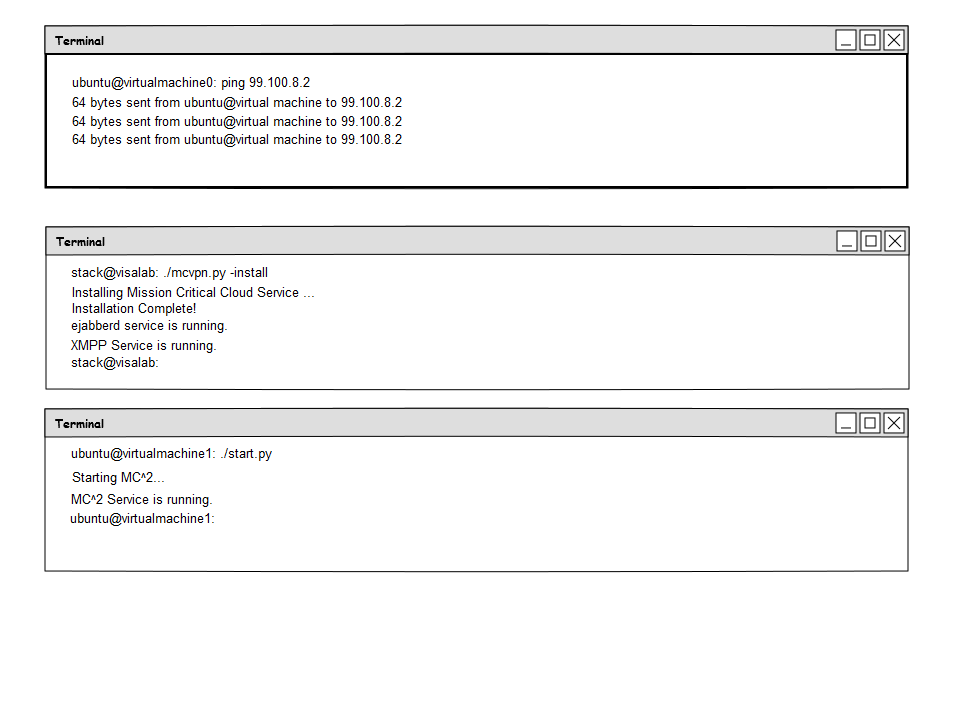


Figure 9.3 - User Interface Mockups

## Appendix D – Analysis models

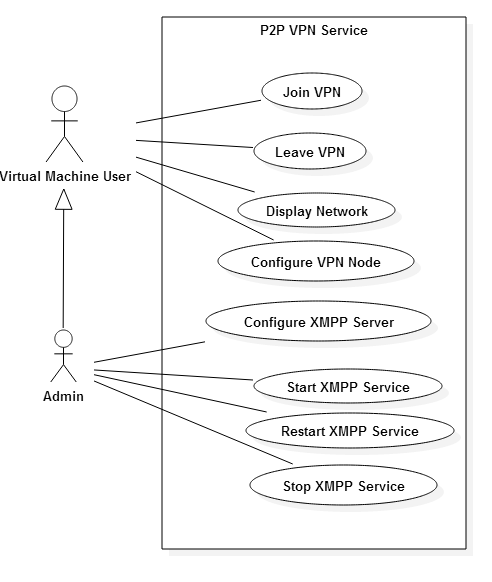


Figure 9.4. - Use Case Diagram

## Appendix E – Design models

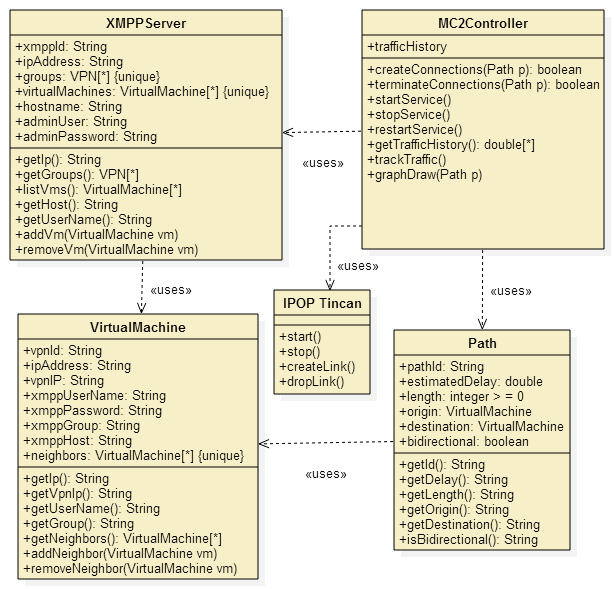


Figure 9.5.1. - Class Diagram

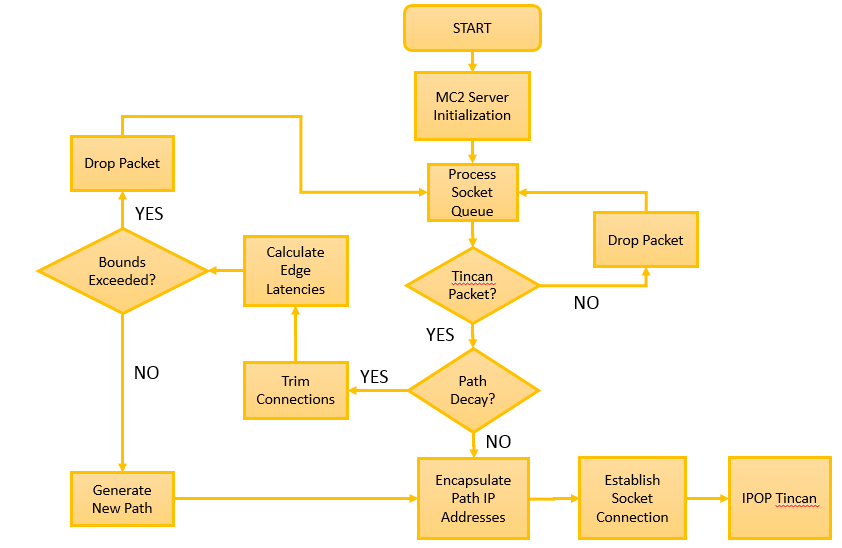


Figure 9.5.2. - Path Generation Control Flow Diagram

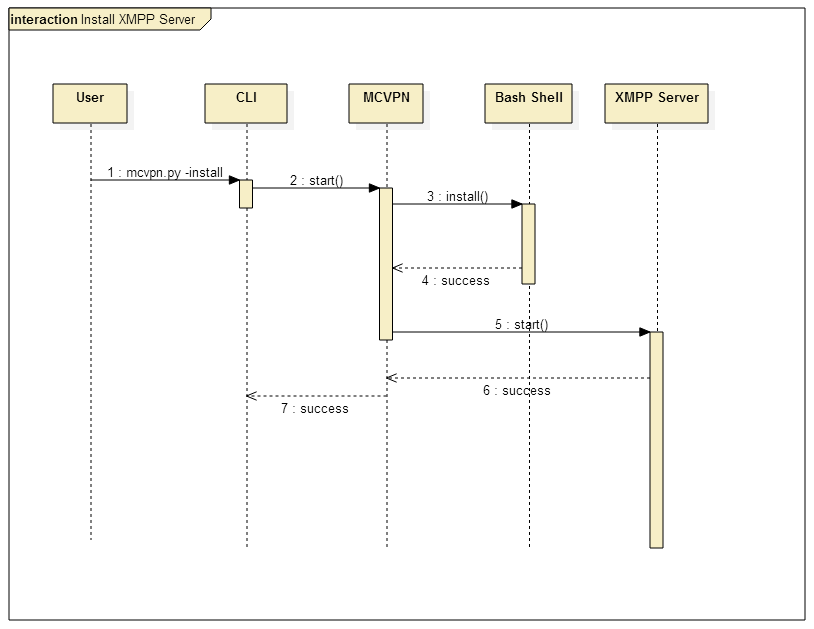


Figure 9.5.3 - Sequence Diagram: Install XMPP Server

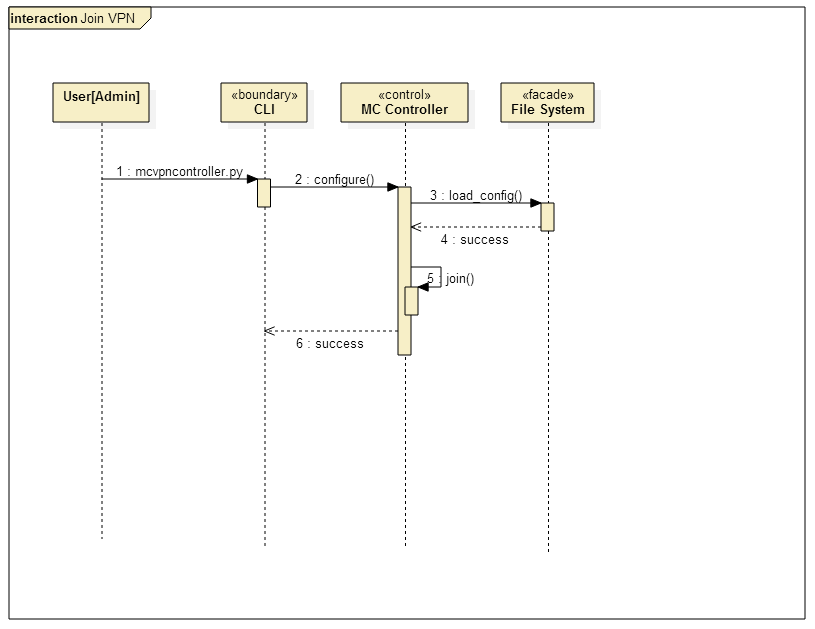


Figure 9.5.4 - Sequence Diagram: Join VPN

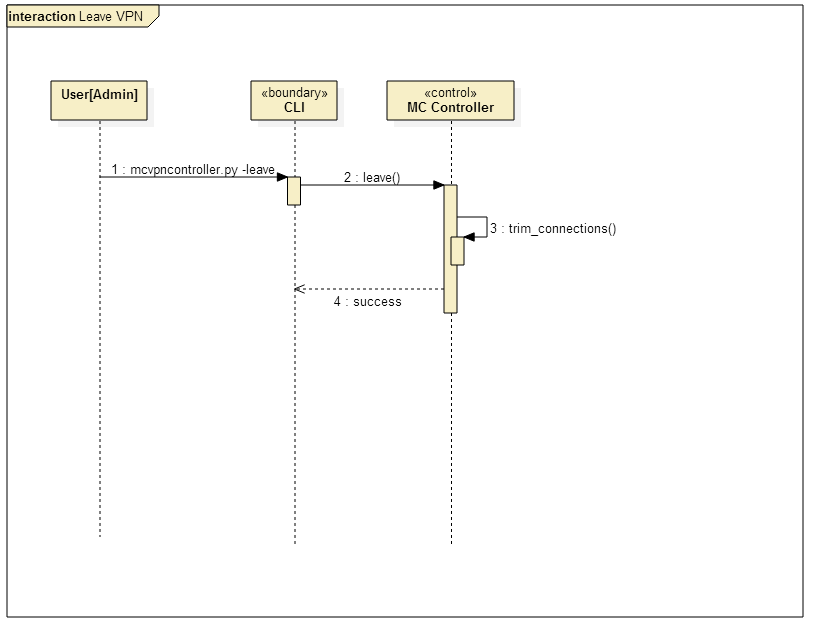


Figure 9.5.5 - Sequence Diagram: Leave VPN

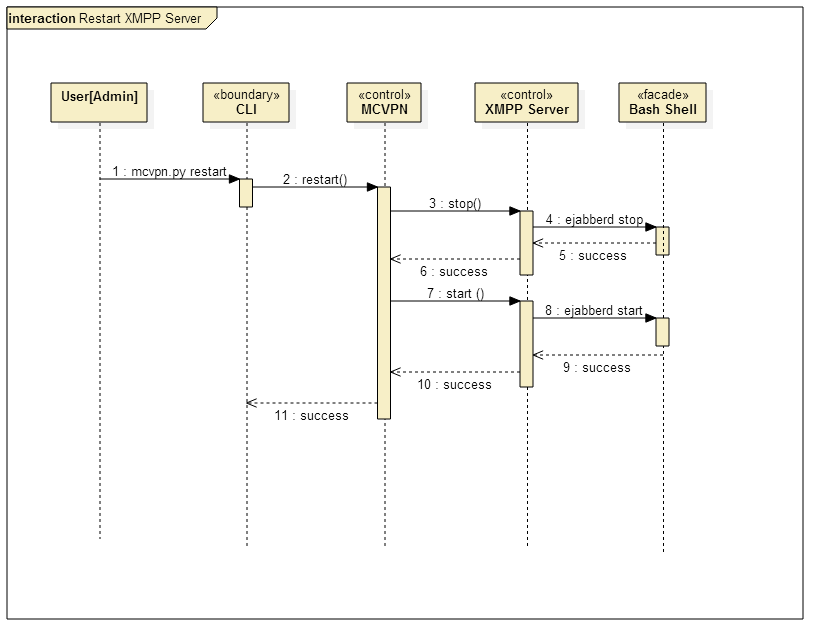


Figure 9.5.6 - Sequence Diagram: Restart XMPP Server

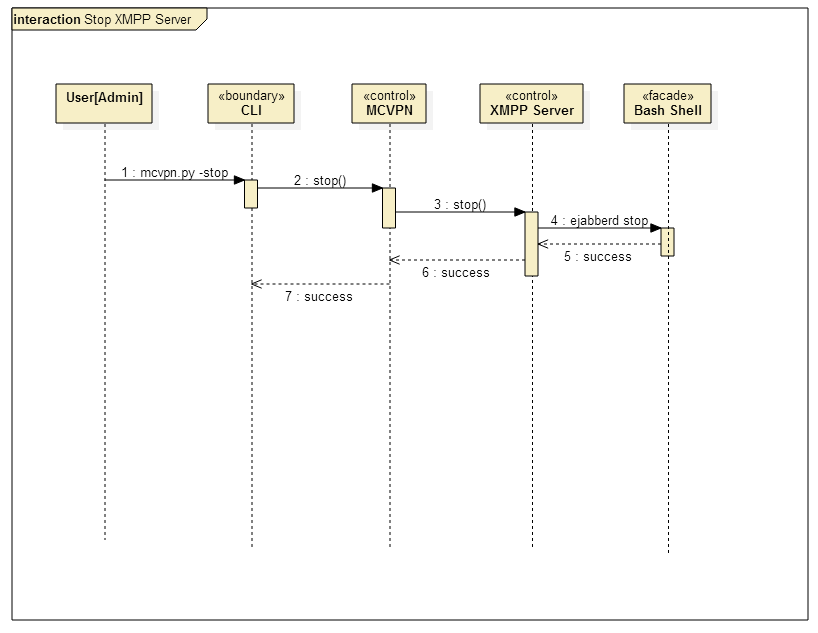


Figure 9.5.7 - Sequence Diagram: Stop XMPP Server

## Appendix F – Documented Class interfaces.

## Appendix G – Documented code for test drivers and stubs.

## Appendix H – Diary of meeting and tasks for the entire semester.

9/05/2014

Present: Dr. Ming Zhao, Francois D’Ugard

Location: ECS 363

Time: 3:00 PM - 3:50 PM

Highlights:

* Discussed Current status of project
* Discussed challenges regarding OpenStack Configuration

9/15/2014

Present: Dr. Ming Zhao, Francois D’Ugard

Location: ECS 363

Time: 12:00 PM - 12:50 PM

Highlights:

* Discussed Current status of project
* Discussed differences between previous project and this semester's senior project.
* Dr. Zhao went into fine detail what differentiates my contributions from the last senior project.
* Z elaborated on the requirements of the new IPOP controller for this iteration of the senior project
* Maintains IPOP sparse network connections to hide or mask controller server
* Controller should use DHT or other algorithm to route messages via existing IPOP VPN links
* Demo application must use the VPN links to route messages among the system.

11/03/2014

Present: Dr. Ming Zhao, Francois D’Ugard

Location: ECS 363

Time: 11:00 AM - 12:00 PM

Highlights:

* Discussed Current status of project
* Dr. Zhao said he would contact Dr. Figueiredo to discuss implementation of message forwarding
* Discussed implementation of message forwarding functionality
* Mentioned encapsulation idea.

Discussed demonstration

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