



# Performance Evaluation with EdgeCloudSim

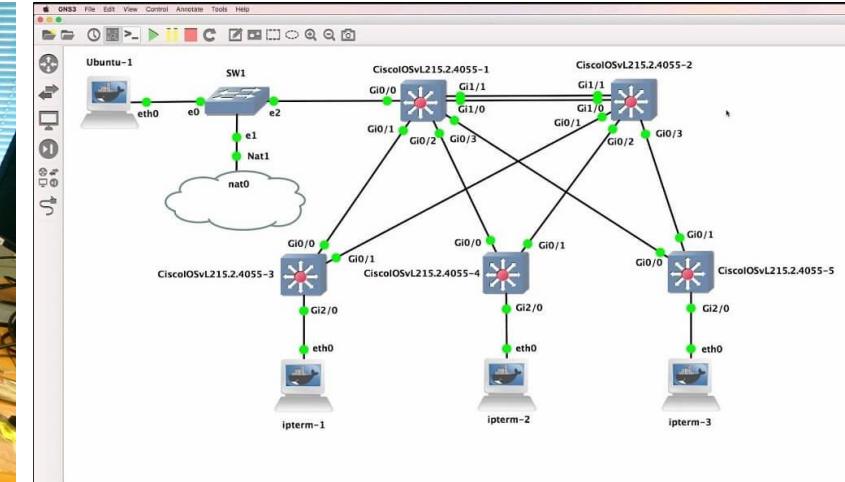
Çağatay Sönmez

27.10.2023

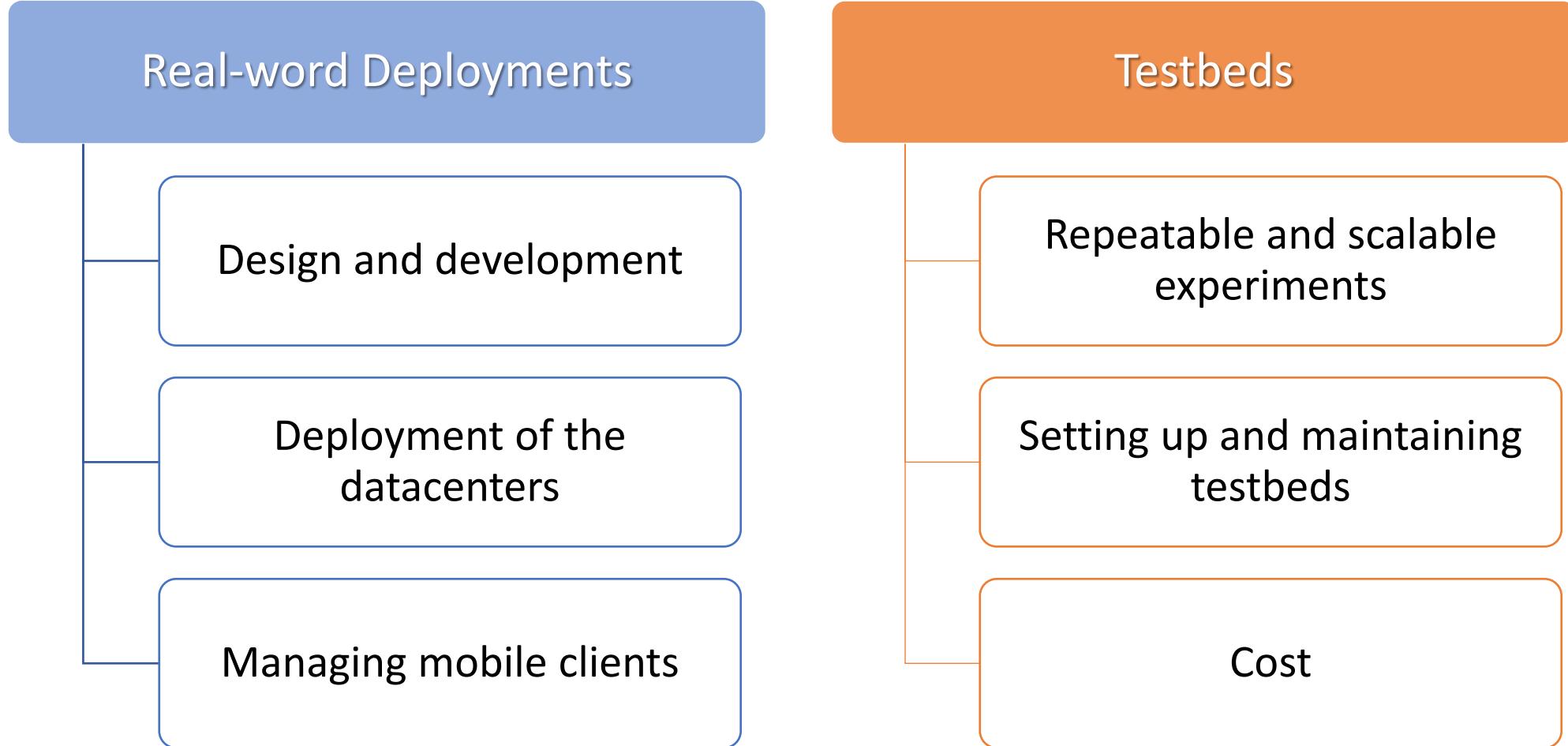
# The Primary Sources Used in This Lecture

- Monika Gill, Dinesh Singh, "**A comprehensive study of simulation frameworks and research directions in fog computing**," *Computer Science Review*, Volume 40, 2021.
- Andras Markus, Attila Kertesz, "**A survey and taxonomy of simulation environments modelling fog computing**", *Simulation Modelling Practice and Theory*, Volume 101, 2020.
- Calheiros, R. N., R. Ranjan, A. Beloglazov, C. A. F. De Rose and R. Buyya, "**CloudSim: A Toolkit for Modeling and Simulation of Cloud Computing Environments and Evaluation of Resource Provisioning Algorithms**", *Softw. Pract. Exper.*, Vol. 41, No. 1, pp. 23–50, Jan. 2011.
- Sonmez, Cagatay, Atay Ozgovde, and Cem Ersoy. "**Edgecloudsim: An environment for performance evaluation of edge computing systems**" *Transactions on Emerging Telecommunications Technologies* 29, no. 11 (2018): e3493.

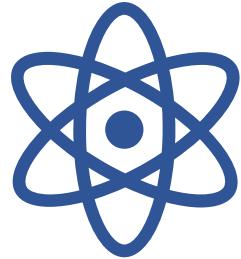
# Reality, Testbeds, Simulators



# Motivation of Using Simulators

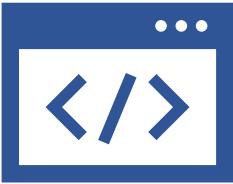


# Methods of Performance Evaluation



## Emulators

- Duplicates all the software, hardware, and operating systems of a real device
- Emulators are more reliable and suitable for debugging
- However, emulators usually runs slow



## Simulators

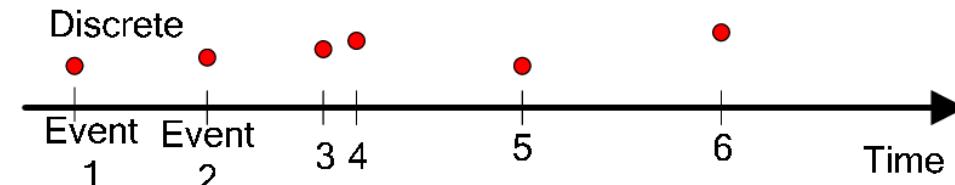
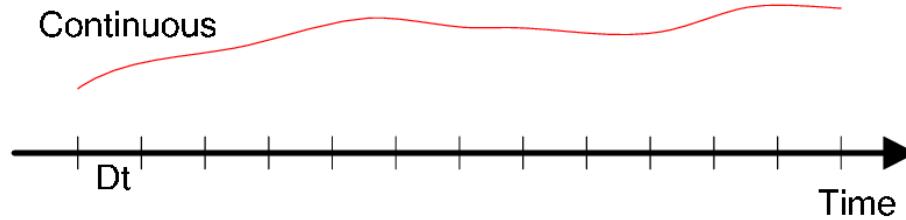
- Creates an environment that mimics the behavior of a real device
- Suitable for rapid prototyping and testing of an idea that has not yet been developed
- However, simulators can sometimes oversimplify the real solution



## Hybrid Models

- In some cases, simulators and emulators are used together. Here, the emulators are used to model the focused area more realistically
- In some studies, the network topology is determined with a simulation study, and then the performance of the relevant topology is evaluated through emulators such as maxinet and mininet

# Continuous-Time and Discrete-Event Models



## Continuous-time simulation

- Tracks system state continuously
- More granular and more accurate but require more computational resources
- Continuous-time simulation is typically applied to natural sciences phenomena like biological, chemical, and environmental processes

## Discrete-event simulation (DES)

- Emphasizes events and state changes
- Uses time skipping; it jumps between changes in the system
- Often relies on queueing theory
- The majority of network and cloud simulators are DES-based.

# CloudSim Simulator

- CloudSim [1] is the most used cloud simulator for typical cloud computing scenarios
- CloudSim is open-source, Java based solution, and it is built on SimJava [2].
- It is mainly designed for modeling Infrastructure as a Service (IaaS) cloud computing environments
- In CloudSim, users define tasks by creating so-called cloudlets
- Cloudlets (tasks) are processed by virtual machines running on cloud resources
- CloudSim also contains a power model, but it is only restricted to CPU energy consumption

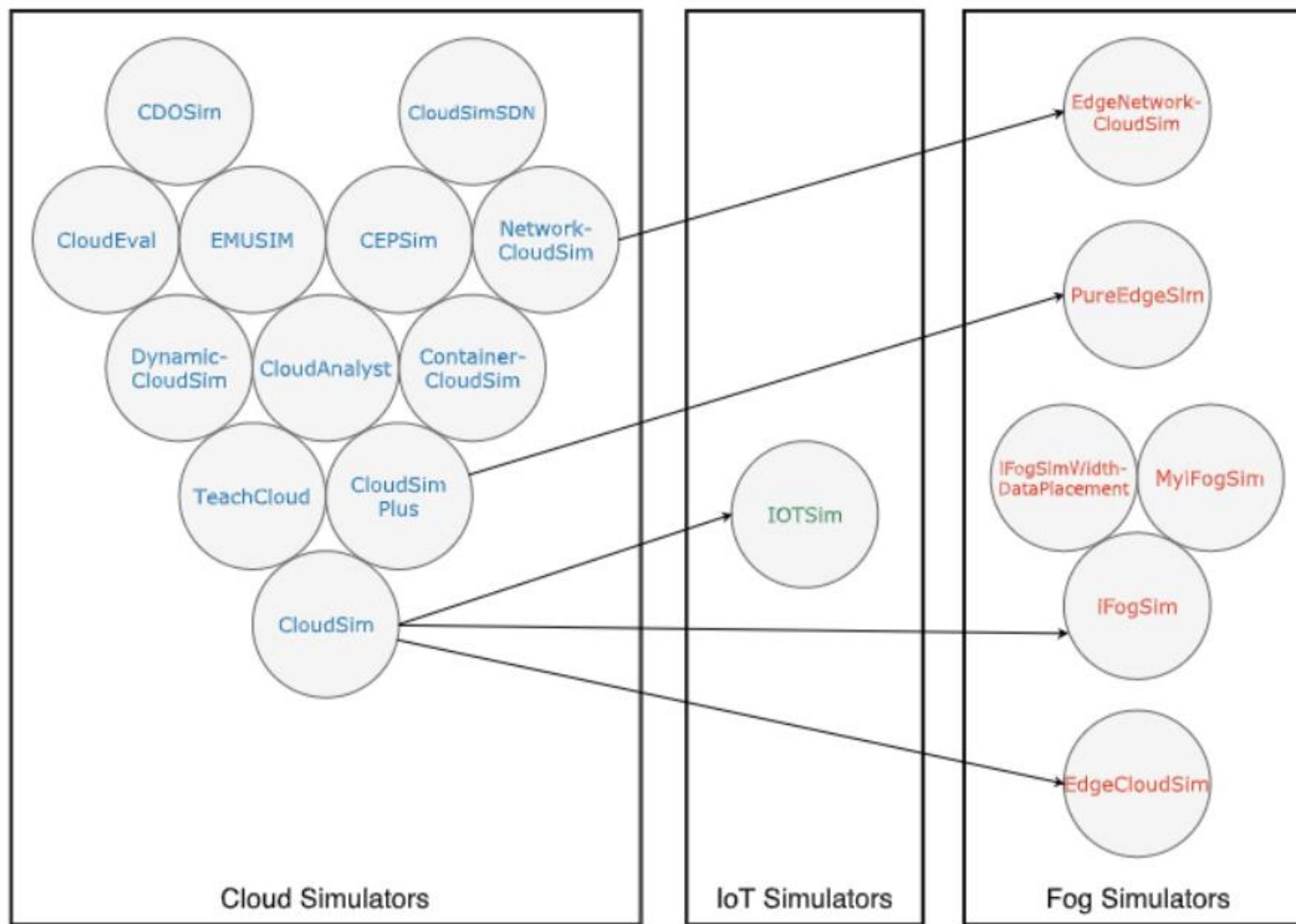
# CloudSim Simulator

cont.

- CloudSim supports both modeling of the cloud components such as datacenters, hosts, and VMs and the resource provisioning policies such as CPU, storage, memory, and bandwidth utilization models
- Using CloudSim for Edge/Fog scenarios brings some difficulties
- Some aspects of the VM utilization model are unrealistic
  - There is no limitation while assigning tasks to VMs
- It does not provide realistic network delay model
  - It uses fixed static variables as network delay
- It does not provide anything related to user mobility

★ There are many extensions of CloudSim, focusing on mostly insufficient features

# Extensions of CloudSim



# CloudSim Core Entities

---

**Datacenter:** Encapsulates a set of compute hosts that can either be homogeneous or heterogeneous with respect to their hardware configurations

---

**Host:** A host is associated to a datacenter. Host executes actions related to management of VMs.

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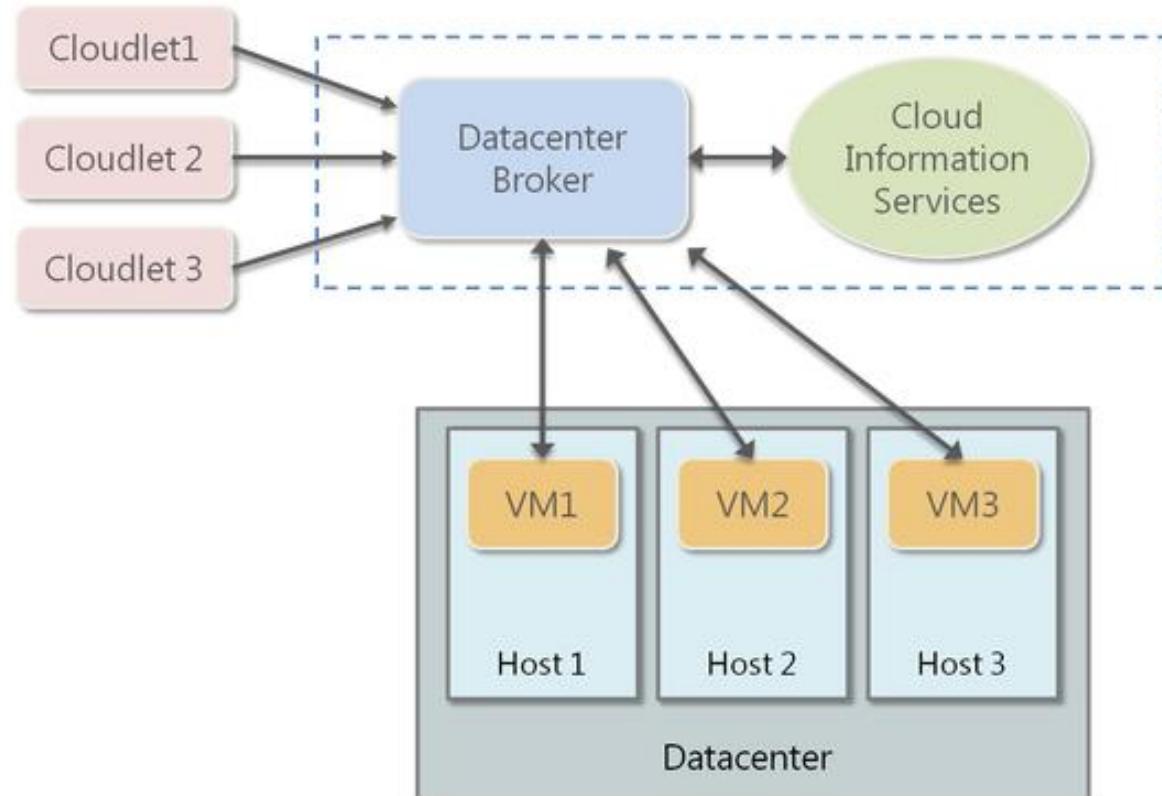
**VM:** A virtual machine models which is managed and hosted by a Cloud host component

---

**Cloudlet:** This term is used as a task in CloudSim. Cloudlet simply represents a task.

---

**DatacenterBroker:** Represents a broker (user) and has two mechanisms for submitting VM provisioning requests to data centers and submitting tasks to VMs.



**Image source:** <https://medium.com/ingkwan/getting-started-with-cloudsim-631e7f6b85d6>

# CloudSim VM and Task Provisioning Policies

- **VM Scheduler**
  - *VmSchedulerSpaceShared*: Only one VM can run on a host's core at a time
  - *VmSchedulerTimeShared*: Dynamically distribute the capacity of a core among
- **Cloudlet Scheduler**
  - *CloudletSchedulerSpaceShared*: Only one task can run on a VM's core at a time
  - *CloudletSchedulerTimeShared*: All tasks can be assigned to the same VM, and they are dynamically context switched during their life cycle

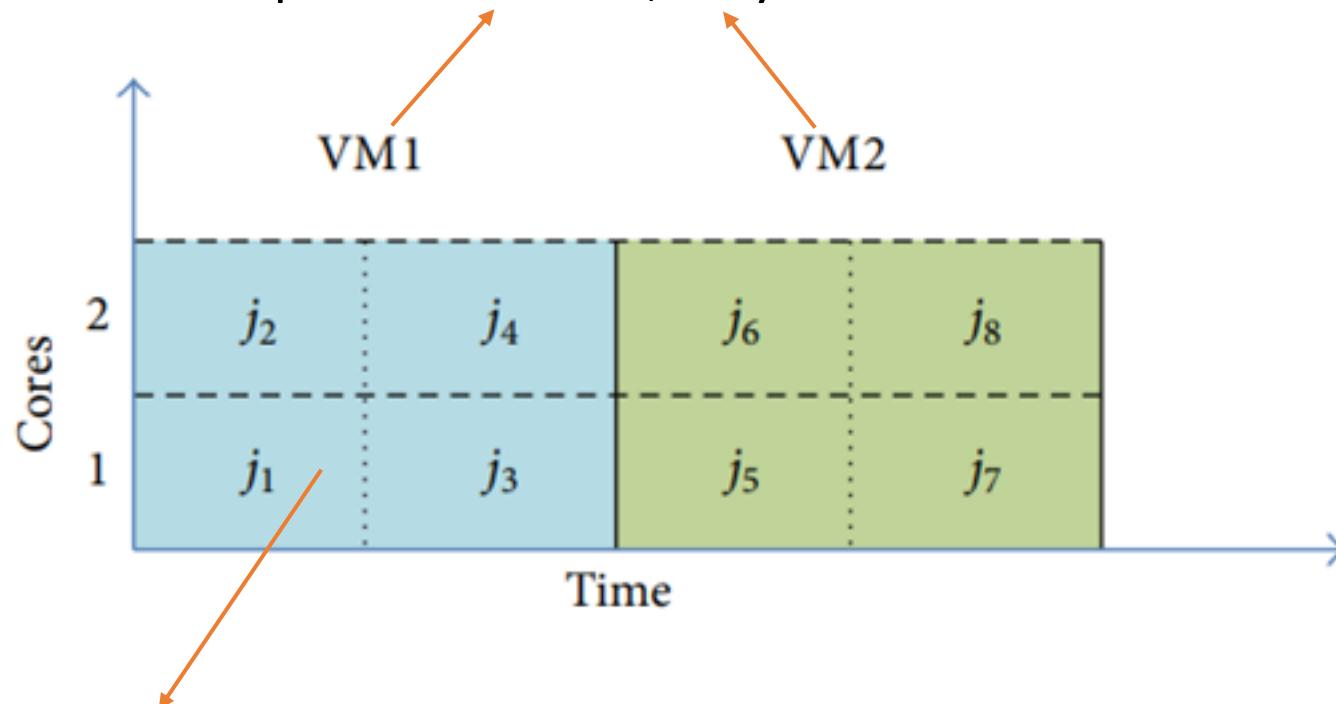
★ **Space Shared** -> queued and executed sequentially

★ **Time Shared** -> run simultaneously by context-switching

# Space-Share Scheduler for VMs and Tasks

- Jobs (tasks)  $j_1, j_2, j_3$ , and  $j_4$  to be hosted in VM1, whereas  $j_5, j_6, j_7$ , and  $j_8$  to be hosted in VM2

As each VM requires two cores, only one VM can run at a time

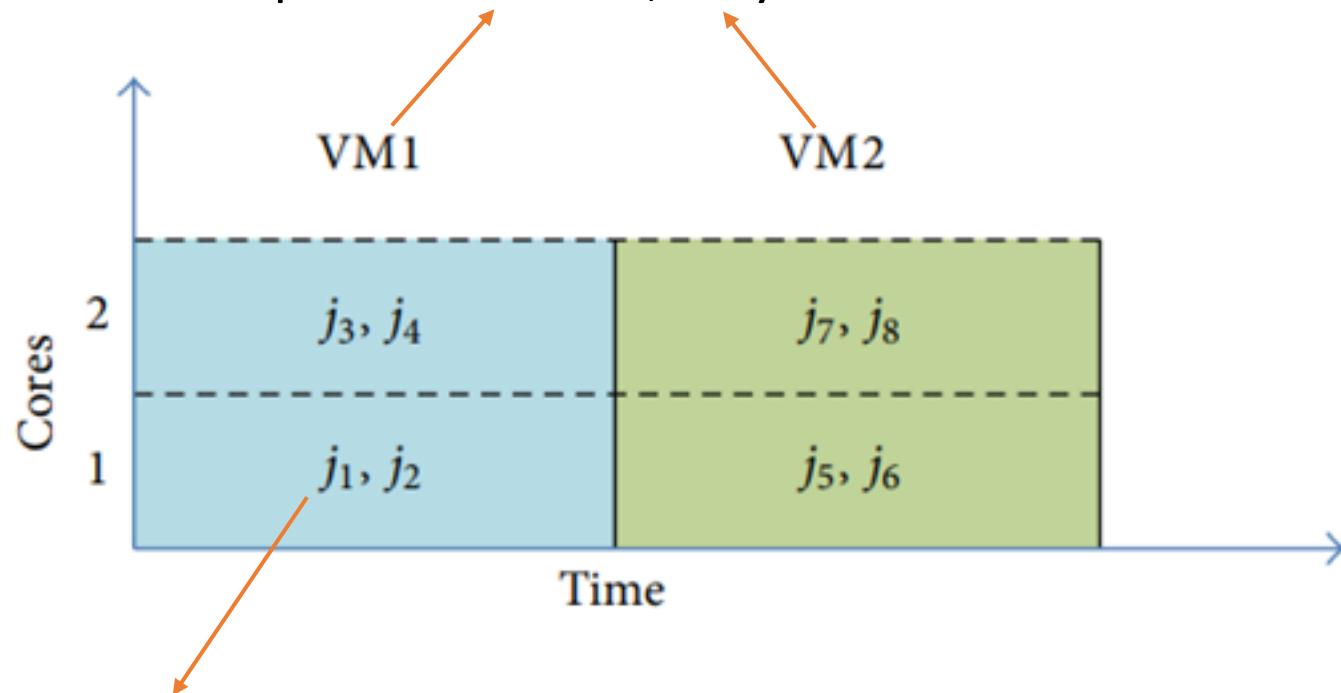


Each job demands only one core,  $j_1$  and  $j_2$  can run simultaneously  
During this period, the  $j_3$  and  $j_4$  wait in the execution queue

# Space-Share for VMs & Time-Shared for Tasks

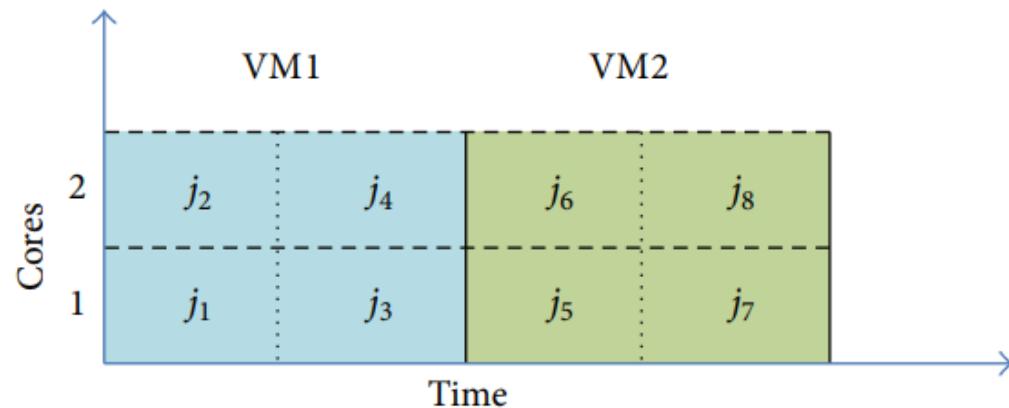
- Jobs (tasks)  $j_1, j_2, j_3$ , and  $j_4$  to be hosted in VM1, whereas  $j_5, j_6, j_7$ , and  $j_8$  to be hosted in VM2

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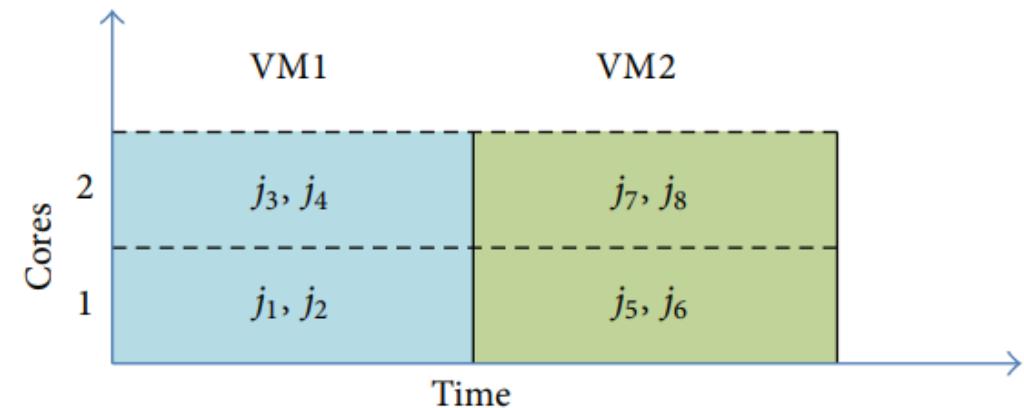


All tasks assigned to VM1 run simultaneously and they are dynamically context switched during their life cycle

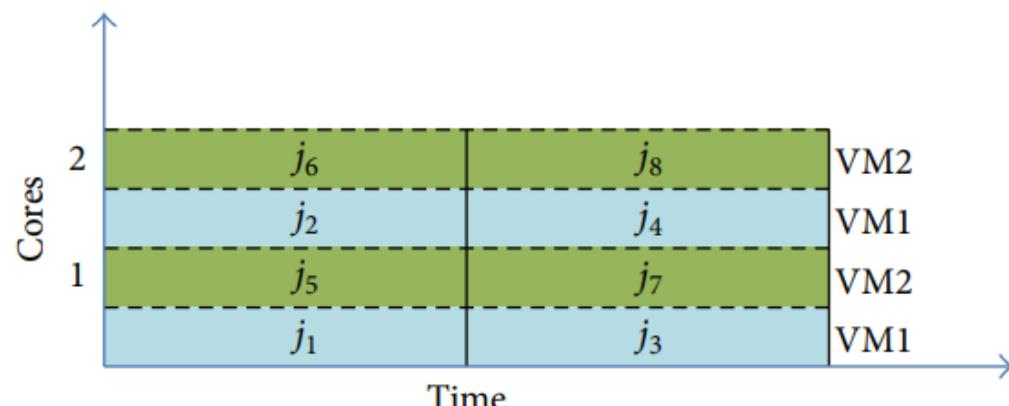
# Time-shared and space-shared policy for VMs and jobs



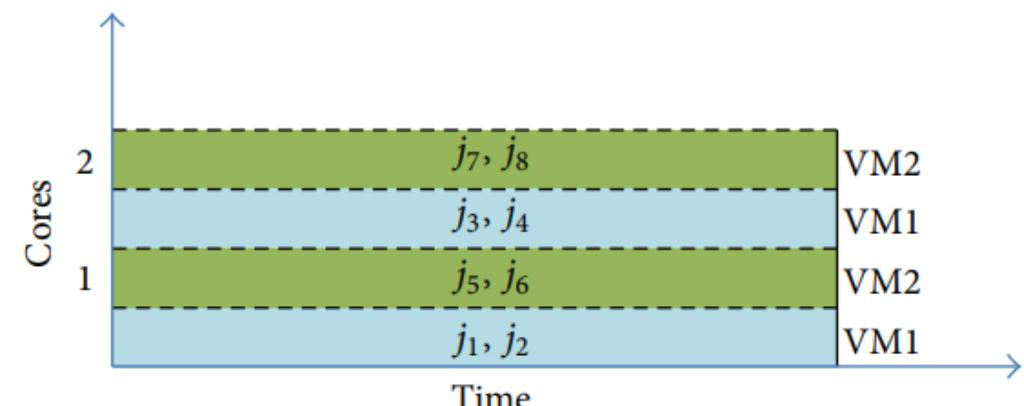
(a)



(b)



(c)



(d)

(a) Space-share for VMs and jobs, (b) space-share for VMs and time-share for jobs, (c) time-share for VMs and space-share for jobs, and (d) time-share for VMs and jobs.

# Characteristic Features of Edge/Fog Simulators

Simulator	Lang.	Type	Core simulator	mobil ity	scalability	Energy + Cost	Network Modelling	Infrastructure entities	Pub. year
iFogSim [3]	Java	Event driven	CloudSim	X	X	E + C	Link bandwidth, delay, network usage	Sensors, Actuators, Fog devices and Datacenters	2017
FogTorch [4]	Java	NA	NA	X	X	X	Latency, bandwidth	Things, Fog and Cloud	2017
EdgeCloudSim [5]	Java	Event driven	CloudSim	✓	X	X	WAN link model, WLAN link model	Mobile client, Edge server, Cloud	2017
FogBus [6]	Java	NA	NA	–	✓	E	Latency, network usage	IoT devices, Fog gw nodes, Fog compute nodes, Cloud datacenter	2018
FogNetSim++ [7]	C++	Network driven	OMNET++	✓	✓	E+C	Packet drop, retransmission, link bandwidth, bit error rate	Mobile end node devices, Fog nodes, Broker nodes, Base stations	2018
Edge-Fog Cloud [8]	Python	NA	NA	X	✓	C	Network cost	Edge, Fog layer and Datastore	2016
FogBed [9]	Python	Emulator	MiniNet & Docker	X	X	–	Service latency	Virtual cloud/fog/edge instance, Virtual switches and links	2018
EmuFog [10]	Java	Emulator	MaxiNet	X	✓	C	Latency	Fog nodes, Network devices(routers)	2017
DEVS for Fog [11]	C++	Event driven	NA	–	–	–	–	User, Broker, Fog, Cloud	2017

# Citations of Simulators Distributed Over the Years

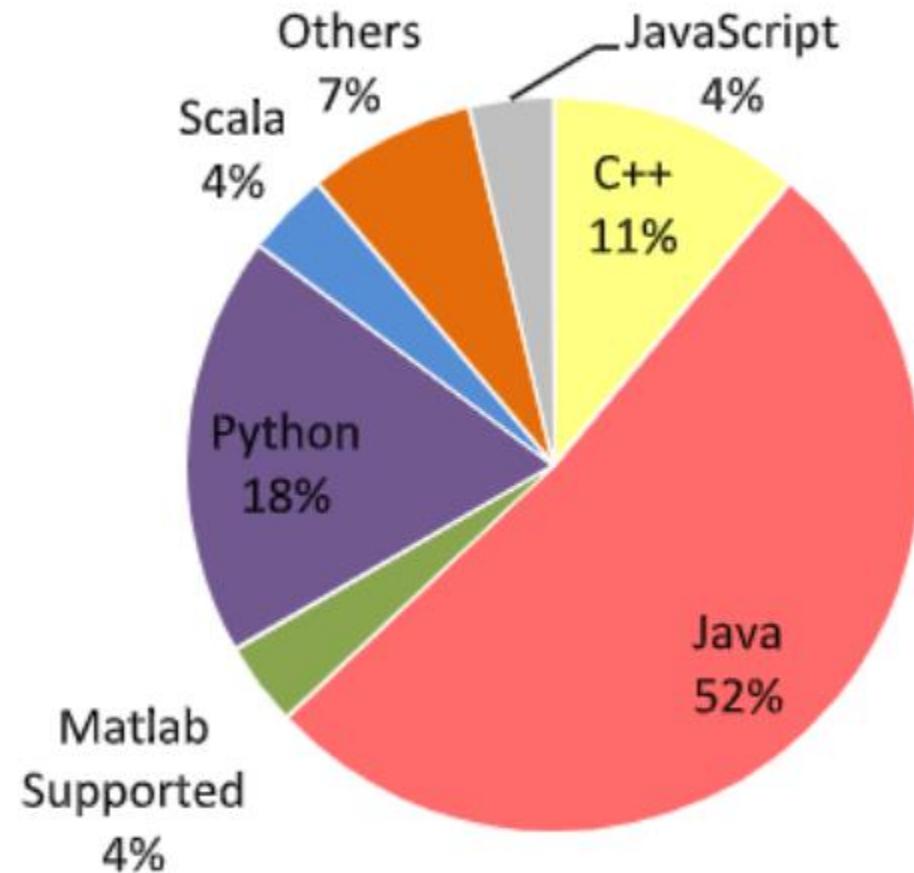
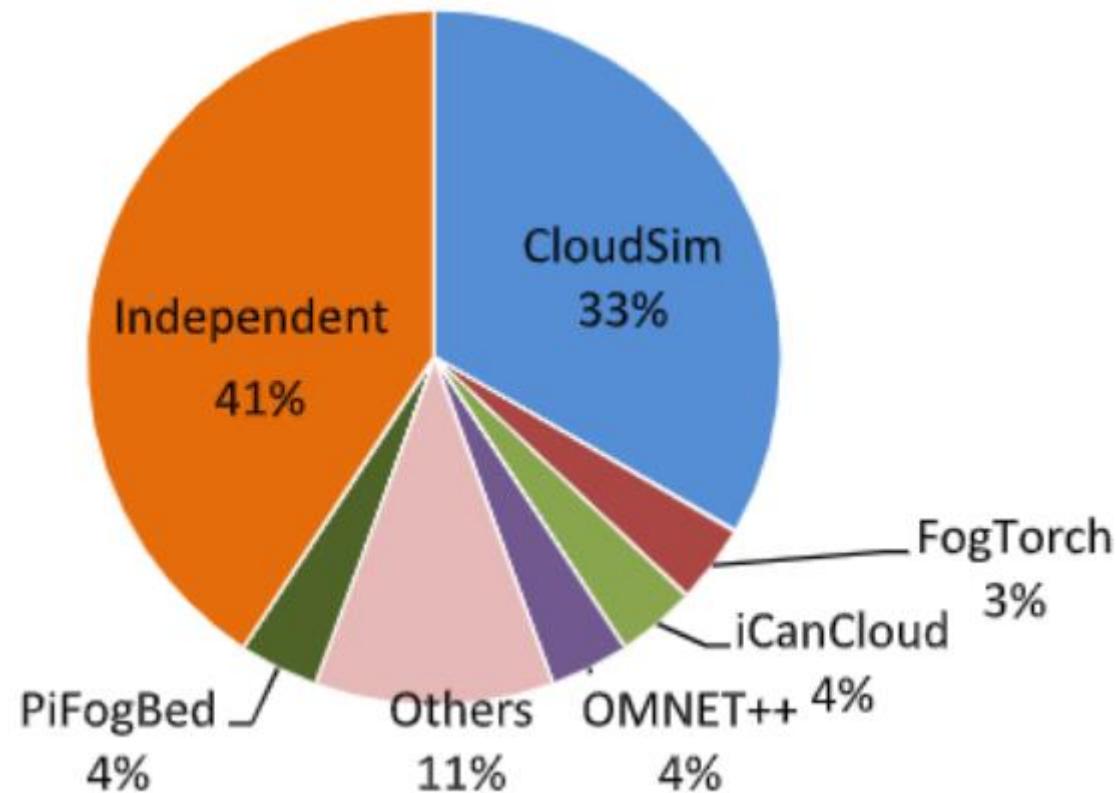


# Open Repositories of Fog/Edge Simulators

Simulator	Source Code	Last Commit	Current Release	# of commits	# of contrib.	License
iFogSim	<a href="https://github.com/Cloudslab/iFogSim1">https://github.com/Cloudslab/iFogSim1</a>	21 Sep. 2016	v2.0	71	2	–
iFogSim2	<a href="https://github.com/Cloudslab/iFogSim">https://github.com/Cloudslab/iFogSim</a>	30 Aug. 2021	v2.0.0	66	1	–
FogTorch	<a href="https://github.com/di-unipi-socc/FogTorch">https://github.com/di-unipi-socc/FogTorch</a>	22 Dec. 2016	NRP	28	1	MIT
EdgeCloudSim	<a href="https://github.com/CagataySonmez/EdgeCloudSim">https://github.com/CagataySonmez/EdgeCloudSim</a>	2 Nov. 2020	v 4.0	42	3	GPL-3.0
FogBus	<a href="https://github.com/shreshhtuli/FogBus">https://github.com/shreshhtuli/FogBus</a>	30 Mar. 2019	v 2.0	199	2	GPL-2.0
FogNetSim++	<a href="https://github.com/rtqayyum/fognetsimpp">https://github.com/rtqayyum/fognetsimpp</a>	5 Dec. 2018	NRP	9	1	GPL-3.0
Edge-Fog Cloud	<a href="https://github.com/nitindermohan/EdgeFogSimulator">https://github.com/nitindermohan/EdgeFogSimulator</a>	17 Oct. 2016	NRP	9	1	GPL-3.0
FogBed	<a href="https://github.com/fogbed/fogbed">https://github.com/fogbed/fogbed</a>	11 Nov. 2018	NRP	2105	35	Mininet 2.3.0d1
EmuFog	<a href="https://github.com/emuFog/emuFog">https://github.com/emuFog/emuFog</a>	28 Sep. 2020	v 2.0	259	2	MIT
DEVS for Fog	<a href="https://www.csit.carleton.ca/~msthalire/FogDEVS/">https://www.csit.carleton.ca/~msthalire/FogDEVS/</a>	23 Sep. 2016	NRP	–	–	–

as of 15 October 2023 (README file updates are ignored), NRP: No Releases Published, Blank(–): Not Available.

# Existing Edge/Fog Simulators & Programming Lang. Used





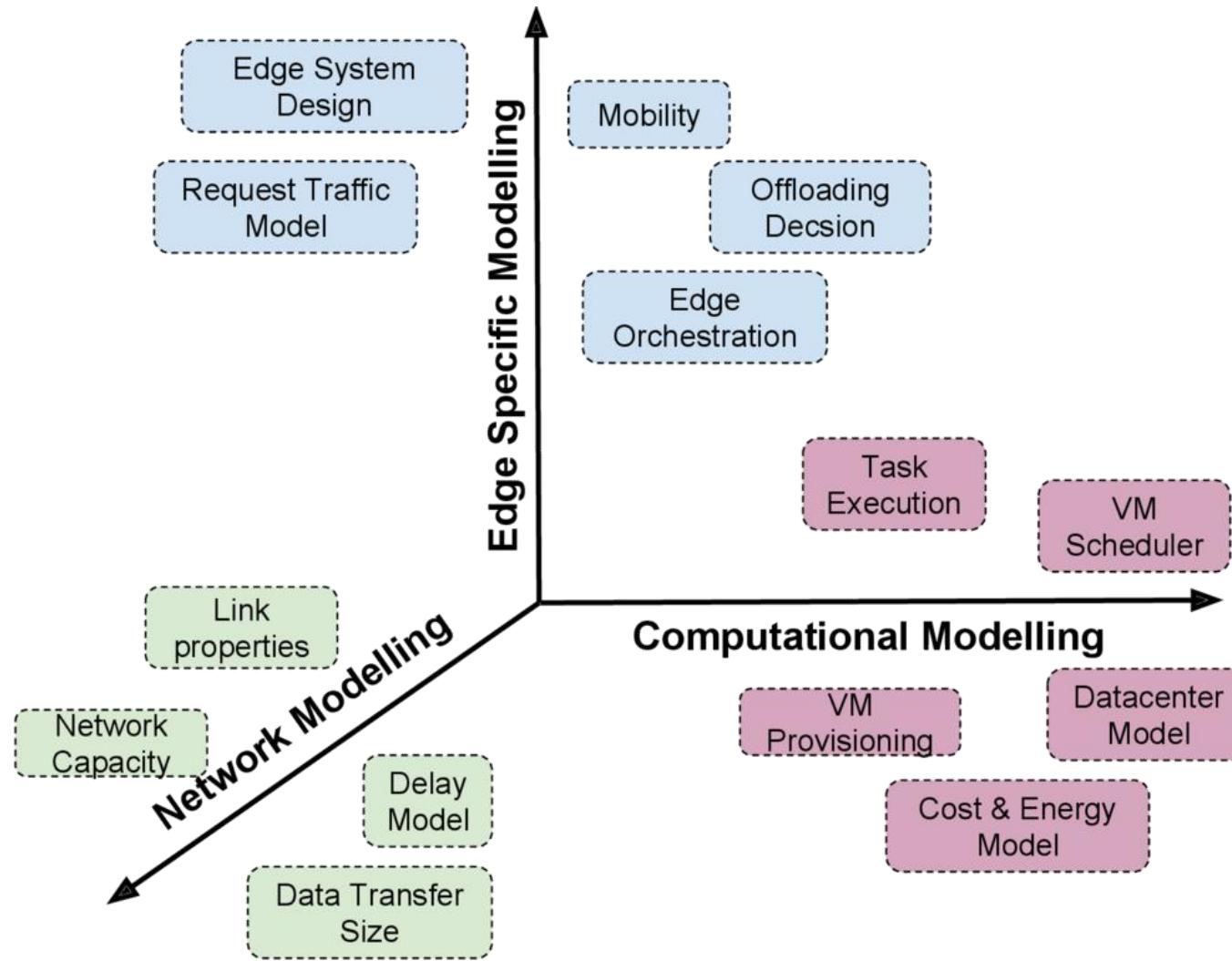
# EdgeCloudSim

C. Sonmez, A. Ozgovde and C. Ersoy, "EdgeCloudSim: An environment for performance evaluation of edge computing systems," *Transactions on Emerging Telecommunications Technologies*, Vol. 29, No. 11, p. e3493, 2018

# What is EdgeCloudSim

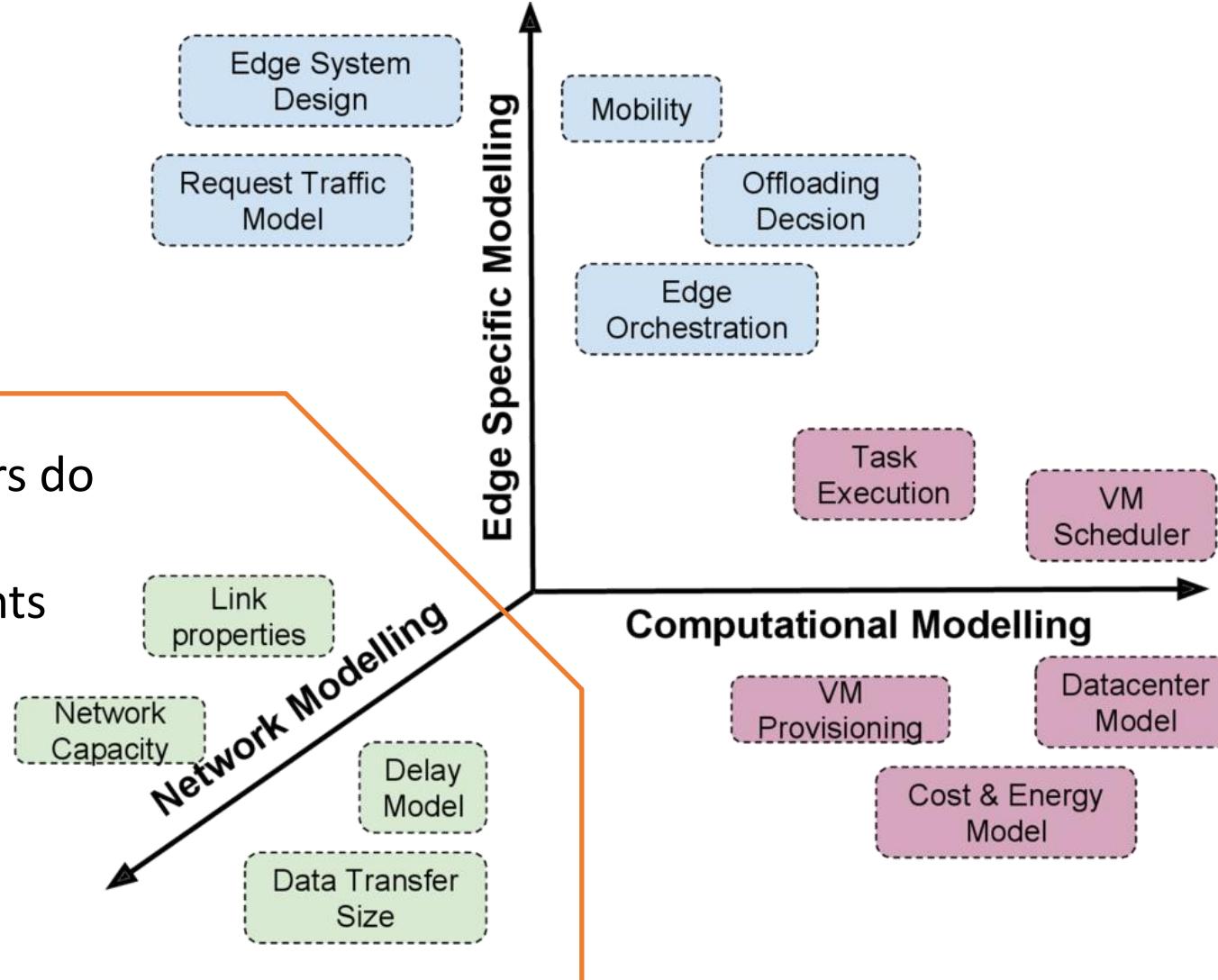
- EdgeCloudSim is a new simulator
- Provides a simulation environment specific to edge computing scenarios
- EdgeCloudSim is based on CloudSim but adds some additional functionalities
- Extensible and easy-to-use
- Publicly available on GitHub
  - <https://github.com/CagataySonmez/EdgeCloudSim>
- Has high reputation; as of October 2023
  - 525 citations based on Google Scholar
  - A discussion forum [11] with 197 members
  - More than 18K views on YouTube channel [12]

# Motivation of Developing a Simulator



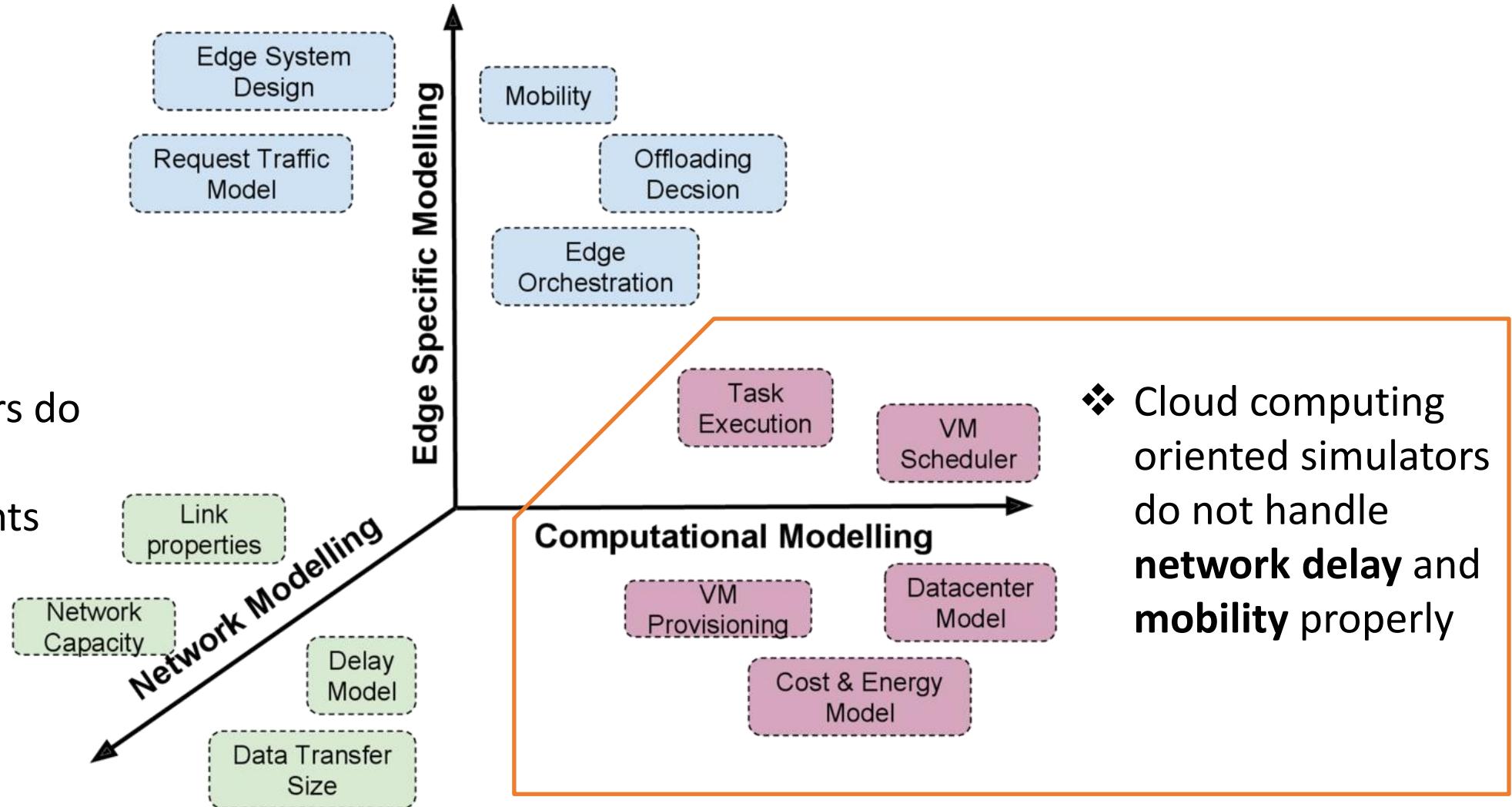
# Motivation of Developing a Simulator

- ❖ Network simulators do not consider cloud computing elements
  - Datacenters
  - Hosts
  - VMs
  - Brokers



# Motivation of Developing a Simulator

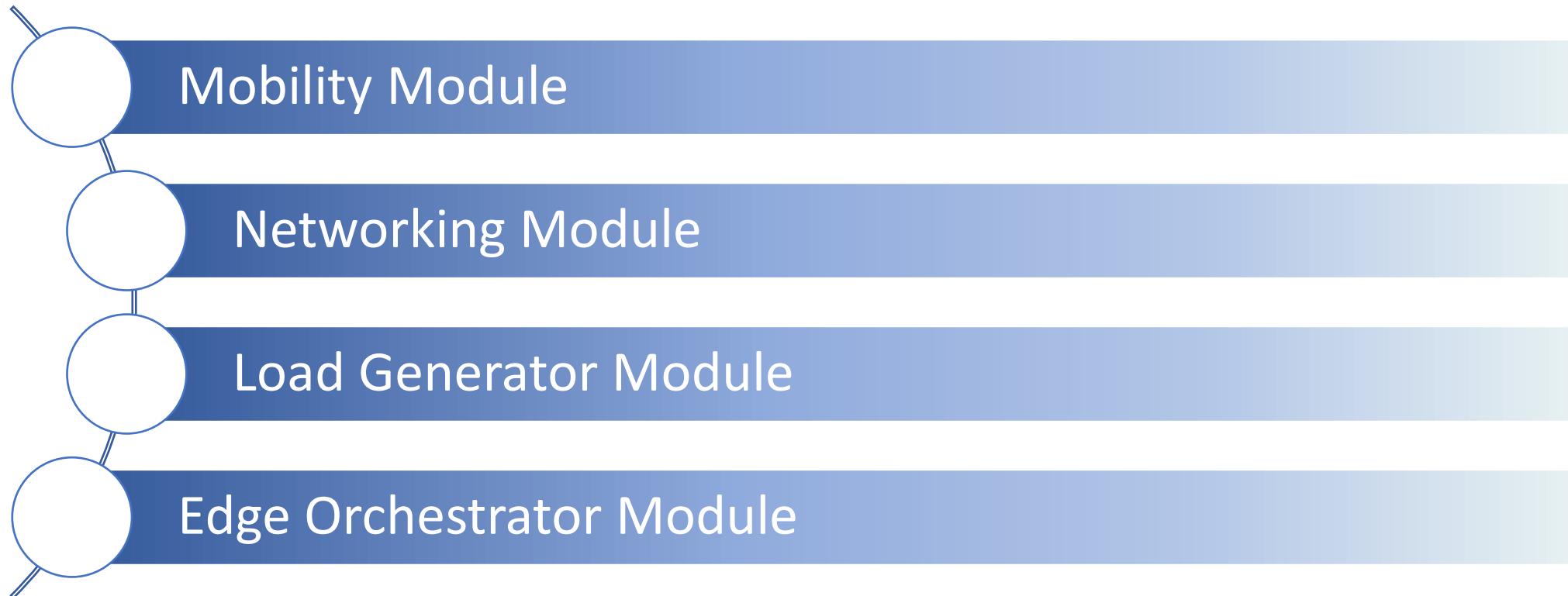
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# Motivation of Developing a Simulator

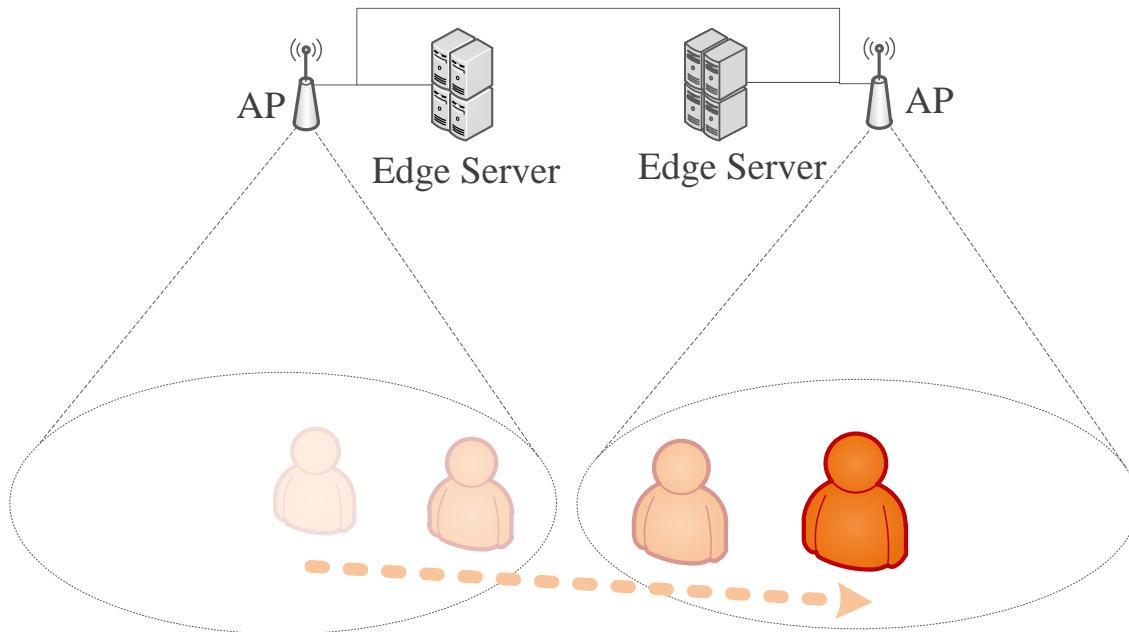
- ❖ Network simulators do not consider cloud computing elements
    - Datacenters
    - Hosts
    - VMs
    - Brokers
  - ❖ There is no easy-to-use simulator for Edge Computing scenarios
  - ❖ Cloud computing oriented simulators do not handle **network delay** and **mobility** properly
- 
- The diagram is a 3D plot with three axes:
- Vertical Axis (Edge Specific Modelling):** Contains boxes for "Edge System Design", "Request Traffic Model", "Mobility", "Offloading Decision", and "Edge Orchestration".
  - Horizontal Axis (Computational Modelling):** Contains boxes for "Task Execution", "VM Scheduler", "VM Provisioning", "Datacenter Model", and "Cost & Energy Model".
  - Diagonal Axis (Network Modelling):** Contains boxes for "Link properties", "Network Capacity", "Delay Model", and "Data Transfer Size".
- A red bracket on the left side groups the first two axes, while a red box encloses the vertical axis.

# EdgeCloudSim Core Modules



## Mobility Module

- Manages the location of edge devices and clients

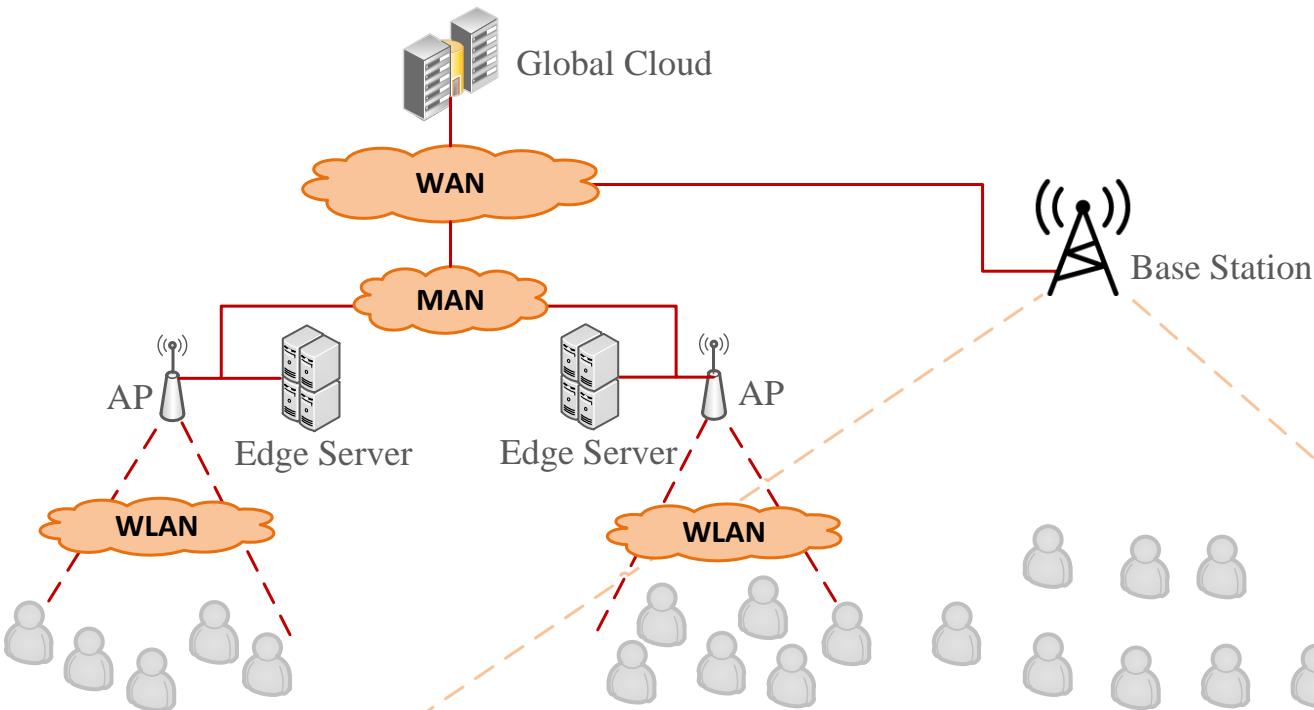


# EdgeCloudSim Core Modules

cont.

## Networking Module

- Adds link delays between the network components

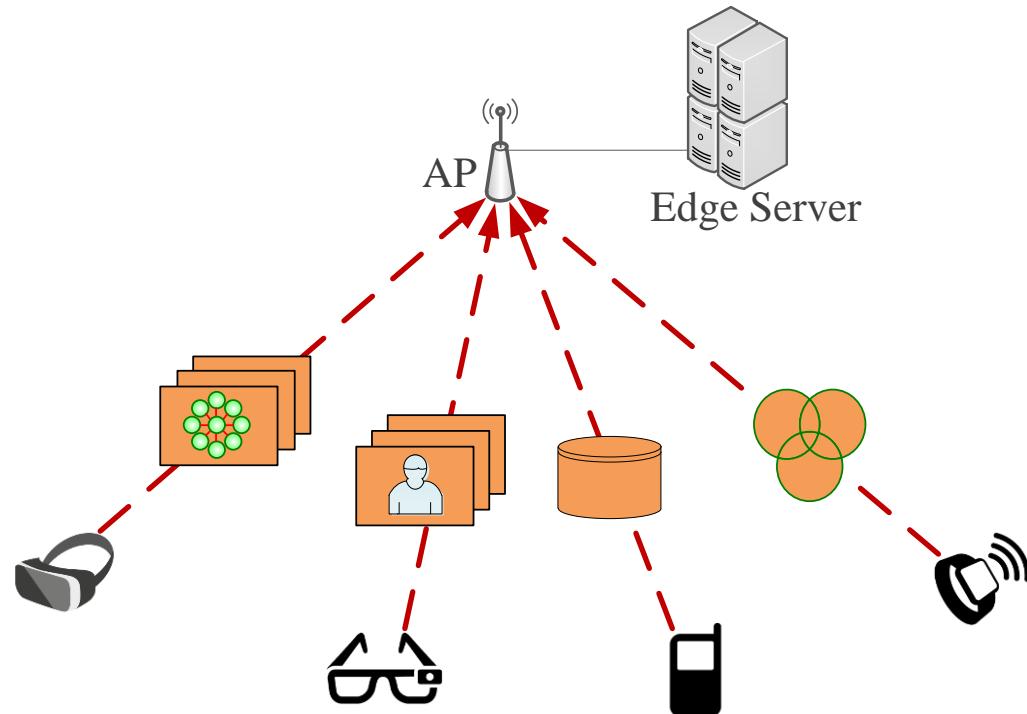


# EdgeCloudSim Core Modules

cont.

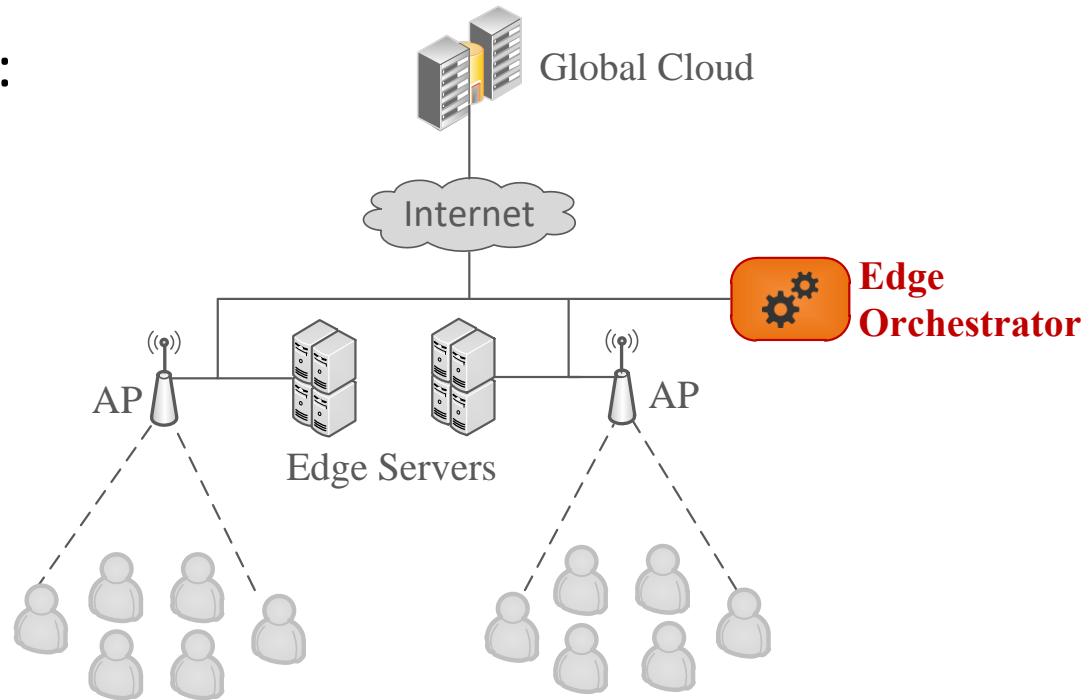
## Load Generator Module

- Generates tasks based on the simulated scenario

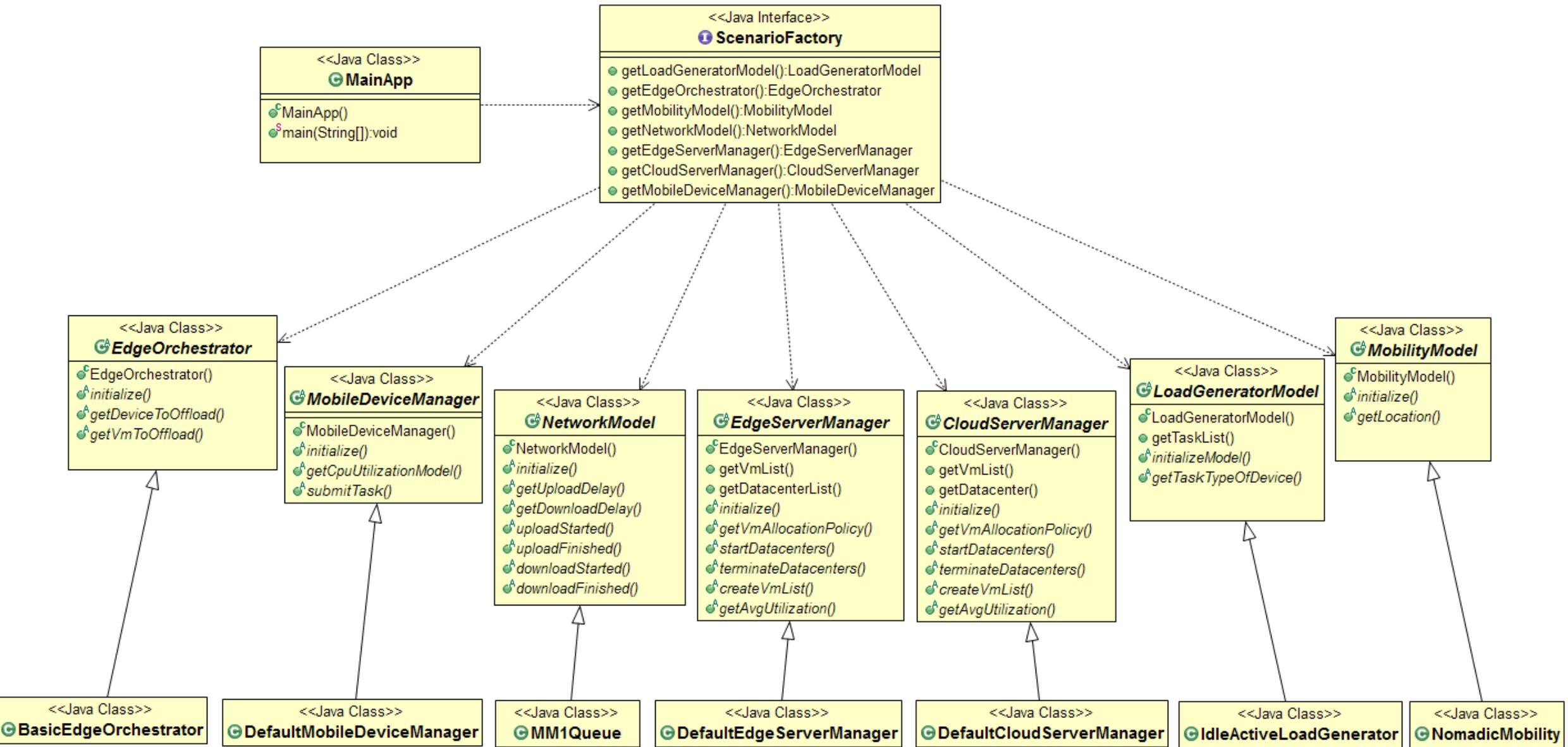


## Edge Orchestrator Module

- The edge orchestrator can be considered as the central nervous system
- It makes critical decisions, such as:
  - Resource provisioning
  - Scales up/down the servers
  - Generates/terminates VMs
  - Migrates tasks
  - Coordinates services



# Extensibility



# Sample Factory Class

---

```
public class VehicularScenarioFactory implements ScenarioFactory {  
    ...  
    @Override  
    public LoadGeneratorModel getLoadGeneratorModel() {  
        return new VehicularLoadGenerator(numOfMobileDevice, simulationTime, simScenario);  
    }  
    @Override  
    public EdgeOrchestrator getEdgeOrchestrator() {  
        return new VehicularEdgeOrchestrator(numOfMobileDevice, orchestratorPolicy, simScenario);  
    }  
    @Override  
    public MobilityModel getMobilityModel() {  
        return new VehicularMobilityModel(numOfMobileDevice, simulationTime);  
    }  
    @Override  
    public NetworkModel getNetworkModel() {  
        return new VehicularNetworkModel(numOfMobileDevice, simScenario, orchestratorPolicy);  
    }  
    @Override  
    public EdgeServerManager getEdgeServerManager() {  
        return new VehicularEdgeServerManager();  
    }  
    @Override  
    public CloudServerManager getCloudServerManager() {  
        return new DefaultCloudServerManager();  
    }  
    @Override  
    public MobileDeviceManager getMobileDeviceManager() throws Exception {  
        return new VehicularMobileDeviceManager();  
    }  
    @Override  
    public MobileServerManager getMobileServerManager() {  
        return new VehicularMobileServerManager(numOfMobileDevice);  
    }  
}
```

# Extending Mobility Model...

---

```
public class VehicularMobilityModel extends MobilityModel {  
    private final double SPEED_FOR_PLACES[] = {20, 40, 60}; //km per hour  
  
    private int lengthOfSegment;  
    private double totalTimeForLoop; //seconds  
    private int[] locationTypes;  
  
    //prepare following arrays to decrease computation on getLocation() function  
    //NOTE: if the number of clients is high, keeping following values in RAM  
    //      may be expensive. In that case sacrifice computational resources!  
    private int[] initialLocationIndexArray;  
    private int[] initialPositionArray; //in meters unit  
    private double[] timeToDriveLocationArray;//in seconds unit  
    private double[] timeToReachNextLocationArray; //in seconds unit  
  
    public VehicularMobilityModel(int _numberOfMobileDevices, double _simulationTime) {  
        super(_numberOfMobileDevices, _simulationTime);  
    }  
  
    @Override  
    public void initialize() {  
        //Find total length of the road  
        Document doc = SimSettings.getInstance().getEdgeDevicesDocument();  
        NodeList datacenterList = doc.getElementsByTagName("datacenter");  
        ...
```

# Extending Network Model...

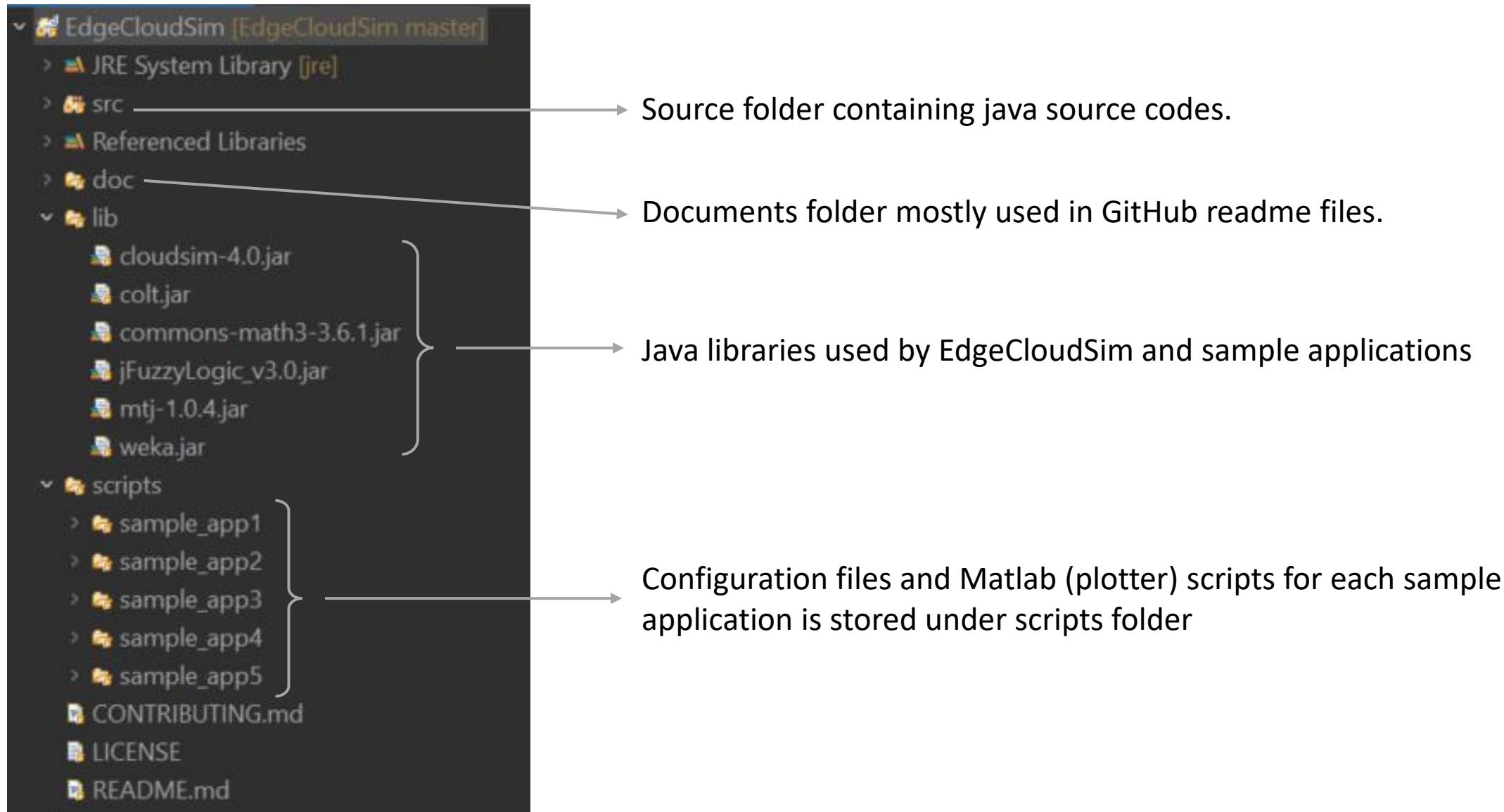
---

```
public class VehicularNetworkModel extends NetworkModel {  
    public static double maxWlanDelay = 0;  
    public static double maxWanDelay = 0;  
    public static double maxGsmDelay = 0;  
  
    private class MMPPWrapper {  
        private double currentPoissonMean;  
        private double currentTaskSize;  
  
        //record last values used for successful packet transmission  
        private double lastPoissonMean;  
        private double lastTaskSize;  
  
        //record last n task statistics during MM1_QUEUE_MODEL_UPDATE.  
        private double numOfTasks;  
        private double totalTaskSize;  
  
        public MMPPWrapper() {  
            currentPoissonMean = 0;  
            currentTaskSize = 0;  
  
            lastPoissonMean = 0;  
            lastTaskSize = 0;  
  
            numOfTasks = 0;  
            totalTaskSize = 0;  
        }  
        ...  
    }
```

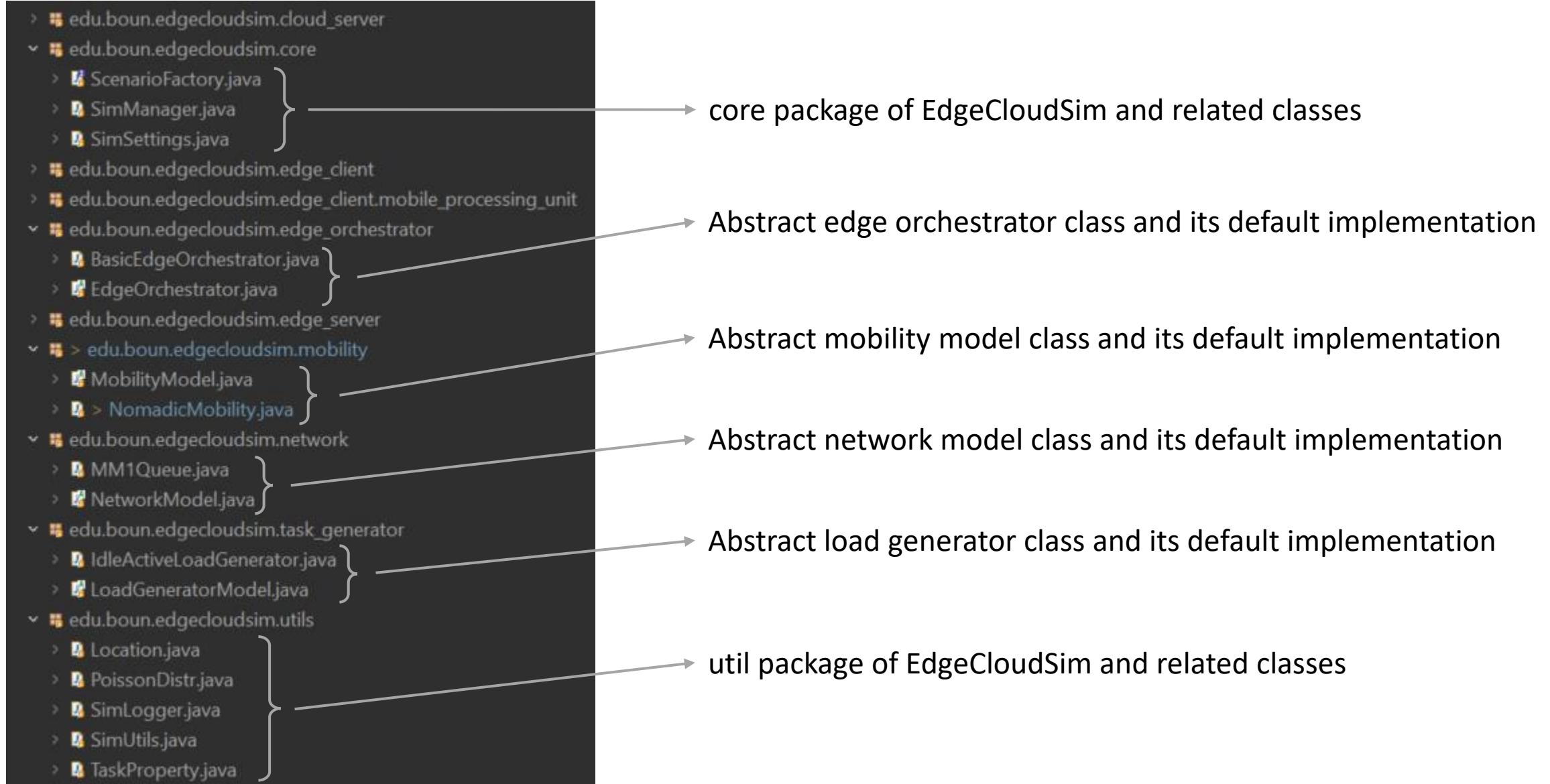
# Downloading EdgeCloudSim

- EdgeCloudSim is publicly available in GitHub
- You should clone EdgeCloudSim repository to start development
  - `$git clone https://github.com/CagataySonmez/EdgeCloudSim.git`
- After cloning the repository, you can use your favorite IDE such as Eclipse and NetBeans
- Please check EdgeCloudSim wiki page for more
  - Using command line
    - <https://github.com/CagataySonmez/EdgeCloudSim/wiki/How-to-compile-EdgeCloudSim-application>
  - Using Eclipse IDE
    - <https://github.com/CagataySonmez/EdgeCloudSim/wiki/EdgeCloudSim-in-Eclipse:-step-by-step-installation-&-running-sample-application>
  - Using Netbeans IDE
    - <https://github.com/CagataySonmez/EdgeCloudSim/wiki/EdgeCloudSim-in-NetBeans:-step-by-step-installation-&-running-sample-application>

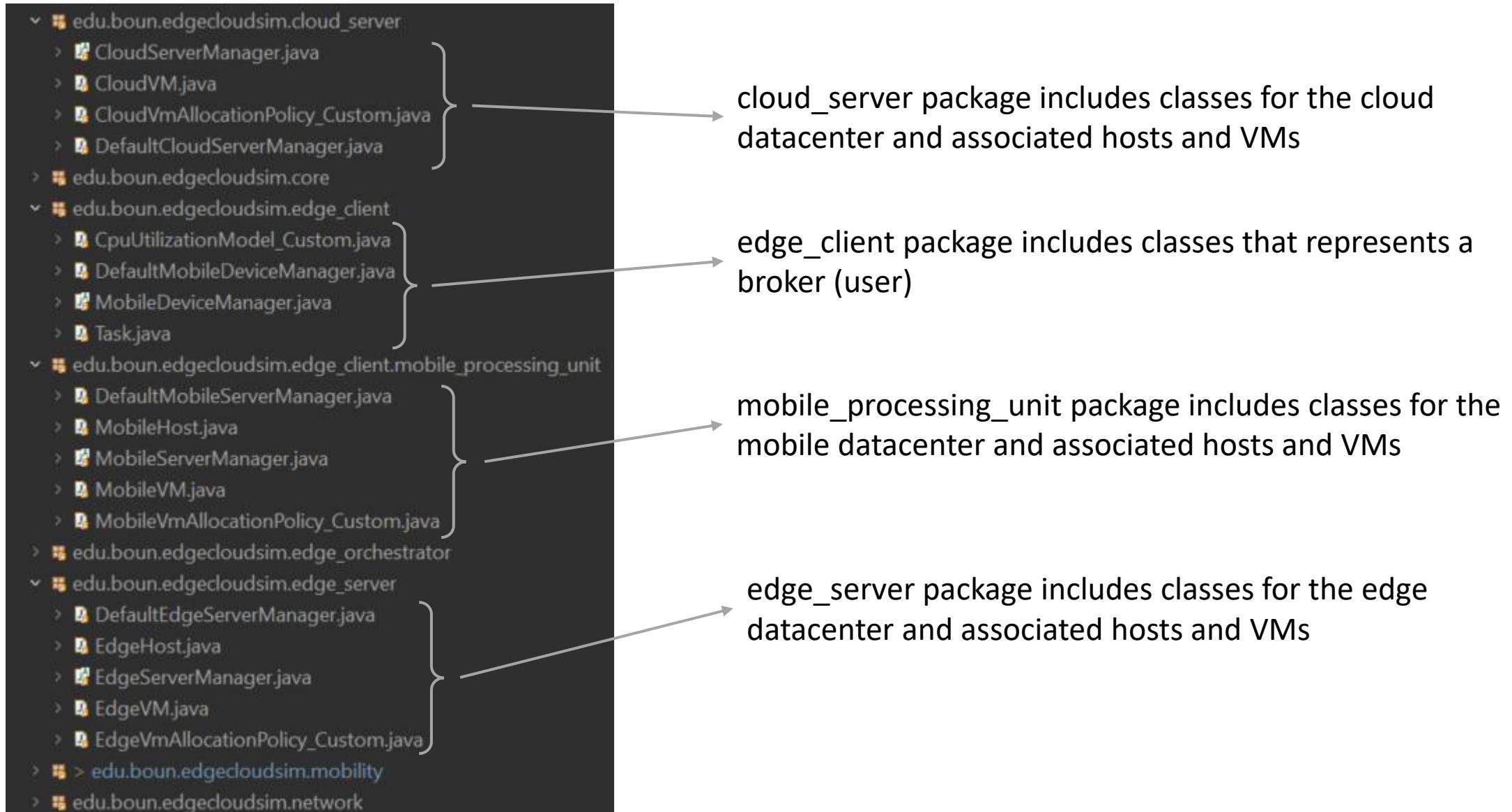
# EdgeCloudSim Folder Hierarchy



# EdgeCloudSim Core Classes



# EdgeCloudSim Computational Classes



# Important Classes: ScenarioFactory

```
public interface ScenarioFactory {  
    /**  
     * provides abstract Load Generator Model  
     */  
    public LoadGeneratorModel getLoadGeneratorModel();  
  
    /**  
     * provides abstract Edge Orchestrator  
     */  
    public EdgeOrchestrator getEdgeOrchestrator();  
  
    /**  
     * provides abstract Mobility Model  
     */  
    public MobilityModel getMobilityModel();  
  
    /**  
     * provides abstract Network Model  
     */  
    public NetworkModel getNetworkModel();  
  
    /**  
     * provides abstract Edge Server Model  
     */  
    public EdgeServerManager getEdgeServerManager();  
  
    /**  
     * provides abstract Cloud Server Model  
     */  
    public CloudServerManager getCloudServerManager();  
  
    /**  
     * provides abstract Mobile Server Model  
     */  
    public MobileServerManager getMobileServerManager();  
  
    /**  
     * provides abstract Mobile Device Manager Model  
     */  
    public MobileDeviceManager getMobileDeviceManager() throws Exception;  
}
```

The ScenarioFactory class provides extensibility. You can provide versions of most of the important classes with different behaviors to implement your simulation scenario.

You have to provide a concrete implementation of ScenarioFactory class to create the SimManager class and run the simulation in your java main method

```
// Generate EdgeCloudsim Scenario Factory  
ScenarioFactory sampleFactory = new SampleScenarioFactory(j, simScen);  
  
// Generate EdgeCloudSim Simulation Manager  
SimManager manager = new SimManager(sampleFactory, j, simScen);  
  
// Start simulation  
manager.startSimulation();
```

Sample code snippet from Java main method

# Important Classes: EdgeOrchestrator

```
package edu.boun.edgecloudsim.edge_orchestrator;  
import org.cloudbus.cloudsim.Vm;  
  
public abstract class EdgeOrchestrator extends SimEntity{  
    protected String policy;  
    protected String simScenario;  
  
    public EdgeOrchestrator(String _policy, String _simScenario){  
        super("EdgeOrchestrator");  
        policy = _policy;  
        simScenario = _simScenario;  
    }  
  
    /*  
     * Default Constructor: Creates an empty EdgeOrchestrator  
     */  
    public EdgeOrchestrator(){  
        super("EdgeOrchestrator");  
    }  
  
    /*  
     * initialize edge orchestrator if needed  
     */  
    public abstract void initialize();  
  
    /*  
     * decides where to offload  
     */  
    public abstract int getDeviceToOffload(Task task);  
  
    /*  
     * returns proper VM from the edge orchestrator point of view  
     */  
    public abstract Vm getVmToOffload(Task task, int deviceId);  
}
```

The edge orchestrator can be considered as the central nervous system. Make all critical decisions here in this class.

You need to extend SimEntity to create custom events!

This generic function is mostly used to decide which task should be sent to which datacenter.

This generic function is mostly used to decide which VM the task should be assigned to.

★ You can add other helper functions in your concrete implementation of this class to handle your business logic!

# Important Classes: MobileDeviceManager

```
package edu.boun.edgecloudsim.edge_client;  
import org.cloudbus.cloudsim.DatacenterBroker;  
  
public abstract class MobileDeviceManager extends DatacenterBroker {  
    public MobileDeviceManager() throws Exception {  
        super("Global_Broker");  
    }  
    /*  
     * initialize mobile device manager if needed  
     */  
    public abstract void initialize();  
    /*  
     * provides abstract CPU Utilization Model  
     */  
    public abstract UtilizationModel getCpuUtilizationModel();  
    public abstract void submitTask(TaskProperty edgeTask);  
}
```

MobileDeviceManager extends CloudSim's DatacenterBroker class which represents a broker (user).

CloudSim does not provide realistic VM CPU utilization model, so that this class is responsible for providing a CPU utilization model based on the simulation scenario

It is basically responsible for submitting VM provisioning requests to data centers (submitting tasks to VMs)



★ For convenience, this class often handles (simulates) the movement of tasks between the entities.

# Important Classes: SimLogger

```
package edu.boun.edgecloudsim.utils;

import java.io.BufferedReader;

public class SimLogger {
    public static enum TASK_STATUS {
        CREATED, UPLOADING, PROCESSING, DOWNLOADING, COMPLETED,
        REJECTED_DUE_TO_VM_CAPACITY, REJECTED_DUE_TO_BANDWIDTH,
        UNFINISHED_DUE_TO_BANDWIDTH, UNFINISHED_DUE_TO_MOBILITY,
        REJECTED_DUE_TO_WLAN_COVERAGE
    }

    public static enum NETWORK_ERRORS {
        LAN_ERROR, MAN_ERROR, WAN_ERROR, GSM_ERROR, NONE
    }

    private long startTime;
    private long endTime;
    private static boolean fileLogEnabled;
    private static boolean printLogEnabled;
    private String filePrefix;
    private String outputFolder;
    private Map<Integer, LogItem> taskMap;
    private LinkedList<VmLoadLogItem> vmLoadList;
    private LinkedList<ApDelayLogItem> apDelayList;

    private static SimLogger singleton = new SimLogger();

    private int numOfAppTypes;

    private File successFile = null, failFile = null;
    private FileWriter successFW = null, failFW = null;
    private BufferedWriter successBW = null, failBW = null;
```

The SimSettings class is located under util package, and responsible for saving simulation results to files.

The first version of SimLogger was logging events to files as they happened, but this approach requires a lot of I/O. Therefore, it was updated to collect the results of the events in data structures and write them to the files at the end of the simulation!

★ SimLogger class is not designed to be extended via the factory pattern; if you need to log different simulation results, you will need to modify this core class!

# Important Classes: SimSettings

```
package edu.boun.edgecloudsim.core;  
  
import java.io.File;  
  
public class SimSettings {  
    private static SimSettings instance = null;  
    private Document edgeDevicesDoc = null;  
  
    public static final double CLIENT_ACTIVITY_START_TIME = 10;  
  
    //predefined IDs for the components.  
    public static final int CLOUD_DATACENTER_ID = 1000;  
    public static final int MOBILE_DATACENTER_ID = 1001;  
    public static final int EDGE_ORCHESTRATOR_ID = 1002;  
    public static final int GENERIC_EDGE_DEVICE_ID = 1003;  
  
    //delimiter for output file.  
    public static final String DELIMITER = ":";  
  
    private double SIMULATION_TIME; //minutes unit in properties file  
    private double WARM_UP_PERIOD; //minutes unit in properties file  
    private double INTERVAL_TO_GET_VM_LOAD_LOG; //minutes unit in proper  
    private double INTERVAL_TO_GET_LOCATION_LOG; //minutes unit in prope  
    private double INTERVAL_TO_GET_AP_DELAY_LOG; //minutes unit in prope  
    private boolean FILE_LOG_ENABLED; //boolean to check file logging op  
    private boolean DEEP_FILE_LOG_ENABLED; //boolean to check deep file  
  
    private int MIN_NUM_OF_MOBILE_DEVICES;  
    private int MAX_NUM_OF_MOBILE_DEVICES;  
    private int MOBILE_DEVICE_COUNTER_SIZE;  
    private int WLAN_RANGE;  
  
    private int NUM_OF_EDGE_DATACENTERS;  
    private int NUM_OF_EDGE_HOSTS;  
    private int NUM_OF_EDGE_VMS;  
    private int NUM_OF_PLACE_TYPES;
```

The SimSettings class is located under core package, and responsible for storing all simulation settings by reading the values in the configuration files.

★ SimSettings class is not designed to be extended via the factory pattern; if you need to store different simulation settings for your simulation scenario, you will need to modify this core class!

# config.properties file

```
#default config file
simulation_time=33
warm_up_period=3
vm_load_check_interval=0.1
location_check_interval=0.1
file_log_enabled=true
deep_file_log_enabled=false

min_number_of_mobile_devices=200
max_number_of_mobile_devices=2000
mobile_device_counter_size=200

wan_propagation_delay=0.1
lan_internal_delay=0.005
wlan_bandwidth=0
wan_bandwidth=0
gsm_bandwidth=0
...
#each mobile device has one host which serves one VM
#all the host runs on a single datacenter due to the
#out of memory (oom) issue
core_for_mobile_vm=1
mips_for_mobile_vm=4000
ram_for_mobile_vm=2000
storage_for_mobile_vm=32000

#use ',' for multiple values
orchestrator_policies=ONLY_EDGE,ONLY_MOBILE,HYBRID

#use ',' for multiple values
simulation_scenarios=MOBILE_PROCESSING_SCENARIO
...
```

Simulation and warm-up time

Values to use for file logging

Number of mobile devices to be used in the simulation

Values to be used in the network model

CPU, memory and storage specifications for mobile devices

Orchestrator policies and scenarios



Any variables related to  
simulation settings are kept in this file

```

<?xml version="1.0"?>
<edge_devices>
    <datacenter arch="x86" os="Linux" vmm="Xen">
        <costPerBw>0.1</costPerBw>
        <costPerSec>3.0</costPerSec>
        <costPerMem>0.05</costPerMem>
        <costPerStorage>0.1</costPerStorage>
        <location>
            <x_pos>1</x_pos>
            <y_pos>1</y_pos>
            <wlan_id>0</wlan_id>
            <attractiveness>0</attractiveness>
        </location>
    </datacenter>
    <hosts>
        <host>
            <core>16</core>
            <mips>80000</mips>
            <ram>16000</ram>
            <storage>400000</storage>
            <VMs>
                <VM vmm="Xen">
                    <core>2</core>
                    <mips>10000</mips>
                    <ram>2000</ram>
                    <storage>50000</storage>
                </VM>
                <VM vmm="Xen">
                    <core>2</core>
                    <mips>10000</mips>
                    <ram>2000</ram>
                    <storage>50000</storage>
                </VM>
            </VMs>
        </host>
    </hosts>
</edge_devices>

```

# edge\_devices.xml file

Bandwidth, CPU, memory and storage cost values for this datacenter (based on CloudSim specifications)

x, y position of the datacenter (will be important for your mobility model)

Each WLAN should have a unique id

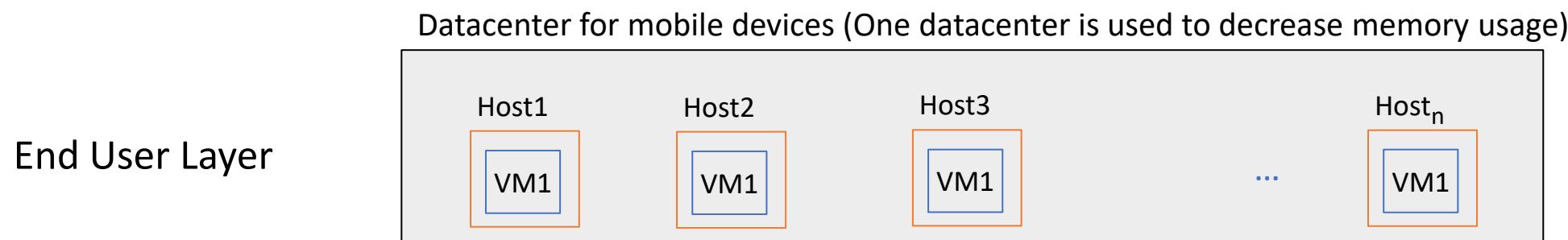
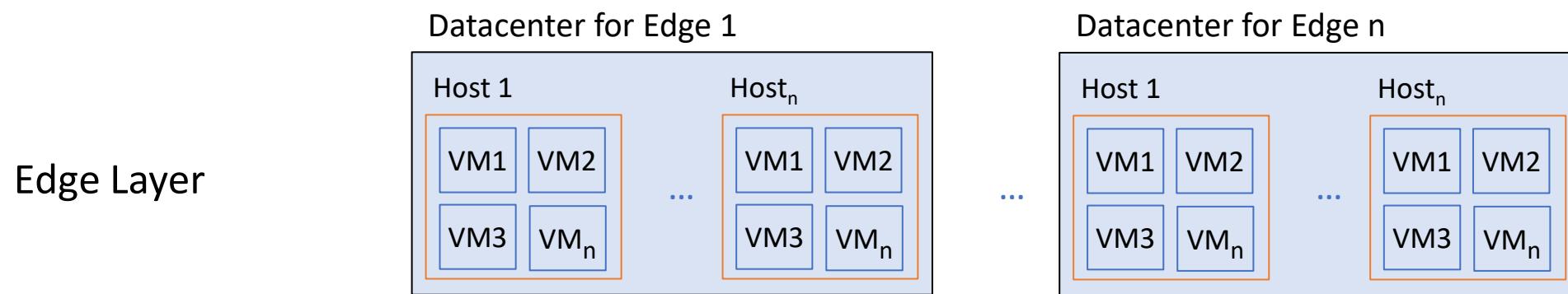
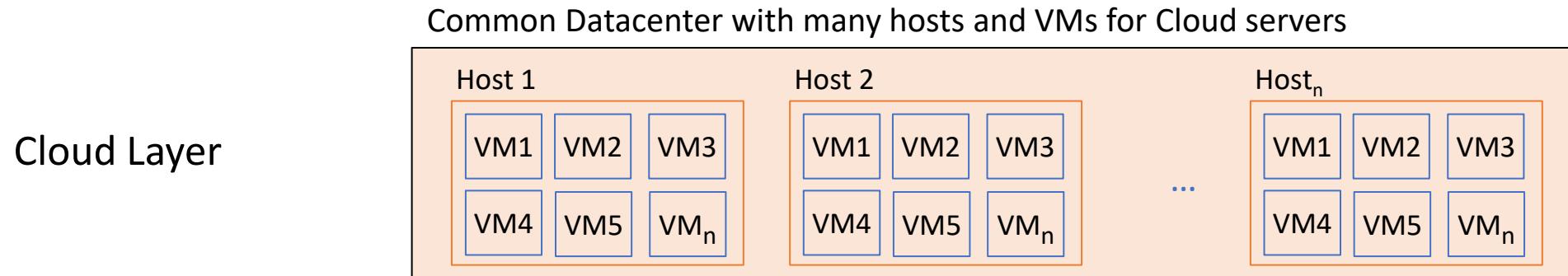
Attractiveness level of this location (for some scenarios)

CPU, memory and storage specifications for the corresponding host

CPU, memory and storage specifications for the corresponding host

★ Edge servers are created with properties specified in this file

# Datacenter, Host and VM Hierarchy in EdgeCloudsim



# applications.xml file

```
<?xml version="1.0"?>
<applications>
  <application name="AUGMENTED_REALITY">
    <usage_percentage>30</usage_percentage>
    <prob_cloud_selection>20</prob_cloud_selection>
    <poisson_interarrival>2</poisson_interarrival>
    <delay_sensitivity>0</delay_sensitivity>
    <active_period>40</active_period>
    <idle_period>20</idle_period>
    <data_upload>1500</data_upload>
    <data_download>250</data_download>
    <task_length>12000</task_length>
    <required_core>1</required_core>
    <vm_utilization_on_edge>8</vm_utilization_on_edge>
    <vm_utilization_on_cloud>0.8</vm_utilization_on_cloud>
    <vm_utilization_on_mobile>20</vm_utilization_on_mobile>
  </application>
  <application name="HEALTH_APP">
    <usage_percentage>20</usage_percentage>
  </application>
</applications>
```

- How much this app is used by mobile devices
- Possibility of offloading to the cloud (for some scenarios)
- Interarrival time for task generation (Poisson process)
- How sensitive the app is to latency (for some scenarios)
- Active period for Active/Idle task generation model
- Idle period for Active/Idle task generation model
- Average size of data loaded by the task
- Average size of data downloaded after the task execution
- Average task length in millions of instructions (MI)
- How much CPU core is used by tasks created by this app
- CPU utilization ratio of related tasks on compute nodes

★ Applications create tasks to be offloaded with the properties specified in this file

```

String configFile = "";
String outputFolder = "";
String edgeDevicesFile = "";
String applicationsFile = "";
if (args.length == 5){
    configFile = args[0];
    edgeDevicesFile = args[1];
    applicationsFile = args[2];
    outputFolder = args[3];
    iterationNumber = Integer.parseInt(args[4]);
}
else{
    SimLogger.println("Simulation setting file, output folder and iteration number not provided via command line arguments. Using static configuration files instead.");
    configFile = "scripts/sample_app1/config/default_config.properties";
    applicationsFile = "scripts/sample_app1/config/applications.xml";
    edgeDevicesFile = "scripts/sample_app1/config/edge_devices.xml";
    outputFolder = "sim_results/ite" + iterationNumber;
}

//load settings from configuration file
SimSettings SS = SimSettings.getInstance();
if(SS.initialize(configFile, edgeDevicesFile, applicationsFile) == false){
    SimLogger.println("cannot initialize simulation settings!");
    System.exit(0);
}

```

# Using Conf. Files

Configuration files are mostly provided via command line arguments (especially when running through terminal).

Sometimes developers can use static file path for convenience (especially when running the simulations through IDEs during development).

SimSettings is initialized with the configuration files

## scripts / sample\_app1 /



config



matlab



.gitignore



compile.sh



run\_scenarios.sh



runner.sh



simulation.list

# Helper Scripts

Each application has utilities in its scripts folder to run simulations and plot results easily

Configuration files located in config folder

MATLAB scripts to generate graphs

Script to compile sample app

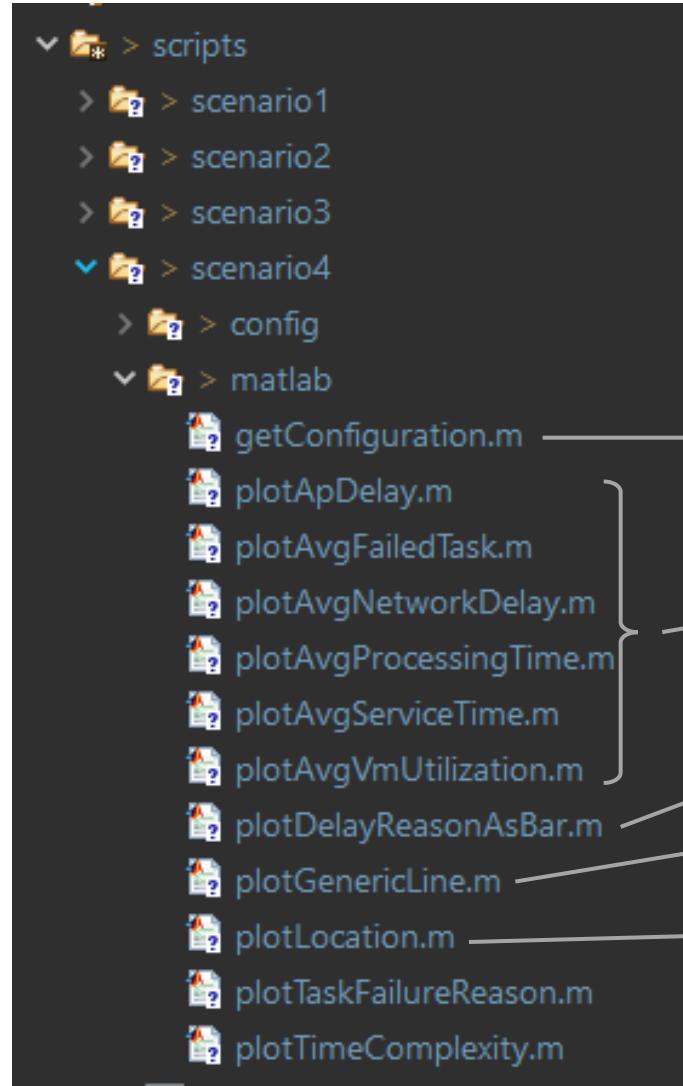
Script to run sample app

Used to run multiple simulations with different configurations (config files)



Scripts are tested & verified on Linux based operating systems including Mac OS

# Plotting Simulation Results



★ First of all, configure getConfiguration.m file based on your simulation scenario and preferences!

→ Configuration file for the other helper scripts

→ Helper scripts to plot graphics using generic line plotter

→ Plots bar graphs for delay types

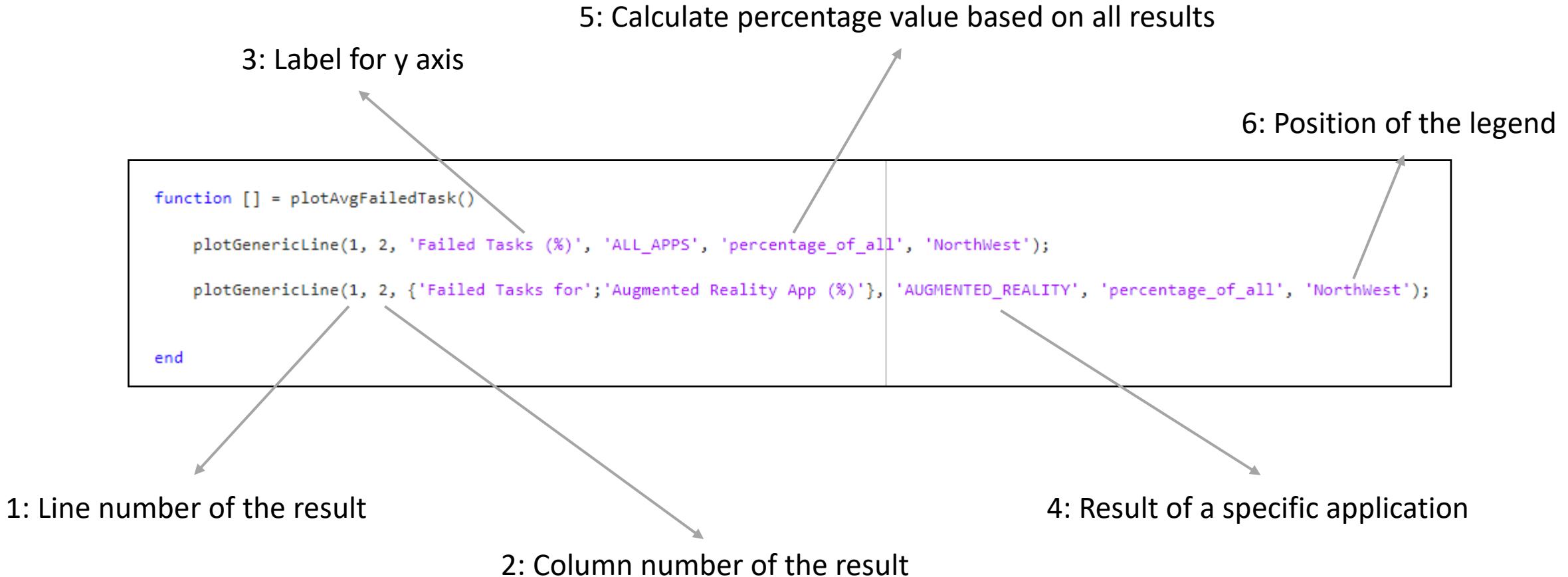
→ Generic line plotter that generates most of the graphics

→ Plots a heat-map like graphics to analyze location of the clients

# Matlab Configuration Script

```
function [ret_val] = getConfiguration(argType)
    if(argType == 1)
        ret_val = '...\\..\\sim_results\\scenario3'; → Folder path where simulation results are saved
    elseif(argType == 2)
        ret_val = 15; %simulation time (in minutes)
    elseif(argType == 3)
        ret_val = 10; %Number of iterations → Number of iterations
    elseif(argType == 4)
        ret_val = 1; %x tick interval for number of mobile devices
    elseif(argType == 5)
        ret_val = {'RANDOM', 'NETWORK_BASED', 'UTILIZATION_BASED'}; → Scenario names used in the simulations
    elseif(argType == 6)
        ret_val = {'rand', 'nw', 'util'}; → Corresponding legend texts in figures
    elseif(argType == 7)
        ret_val=[6 3 15 15]; %position of figure
    elseif(argType == 8)
        ret_val = [13 12 12]; %font size for x/y label, legend and x/y } → Position, size and font size of graphs
    elseif(argType == 9)
        ret_val = 'Number of Clients'; %Common text for x axis → Common x axis label
    elseif(argType == 10)
        ret_val = 200; %min number of mobile device
    elseif(argType == 11)
        ret_val = 200; %step size of mobile device count } → Number of clients used in the simulation
    elseif(argType == 12)
        ret_val = 2000; %max number of mobile device
    elseif(argType == 17)
        ret_val = 0; %return 1 if you want to add 10^n text at x axis
    elseif(argType == 18)
        ret_val = 0; %return 1 if you want to save figure as pdf → Option to save graph in pdf format
    elseif(argType == 19)
        ret_val = 1; %return 1 if you want to plot errors → Option to plot graphs with 95% confidence interval error bars
    elseif(argType == 20)
        ret_val= 1; %return 1 if graph is plotted colorful → Option to plot graph in color
    elseif(argType == 21)
```

# Sample Plotter Script



# Live Demo Session



# Case Study 1 – VM Scheduling

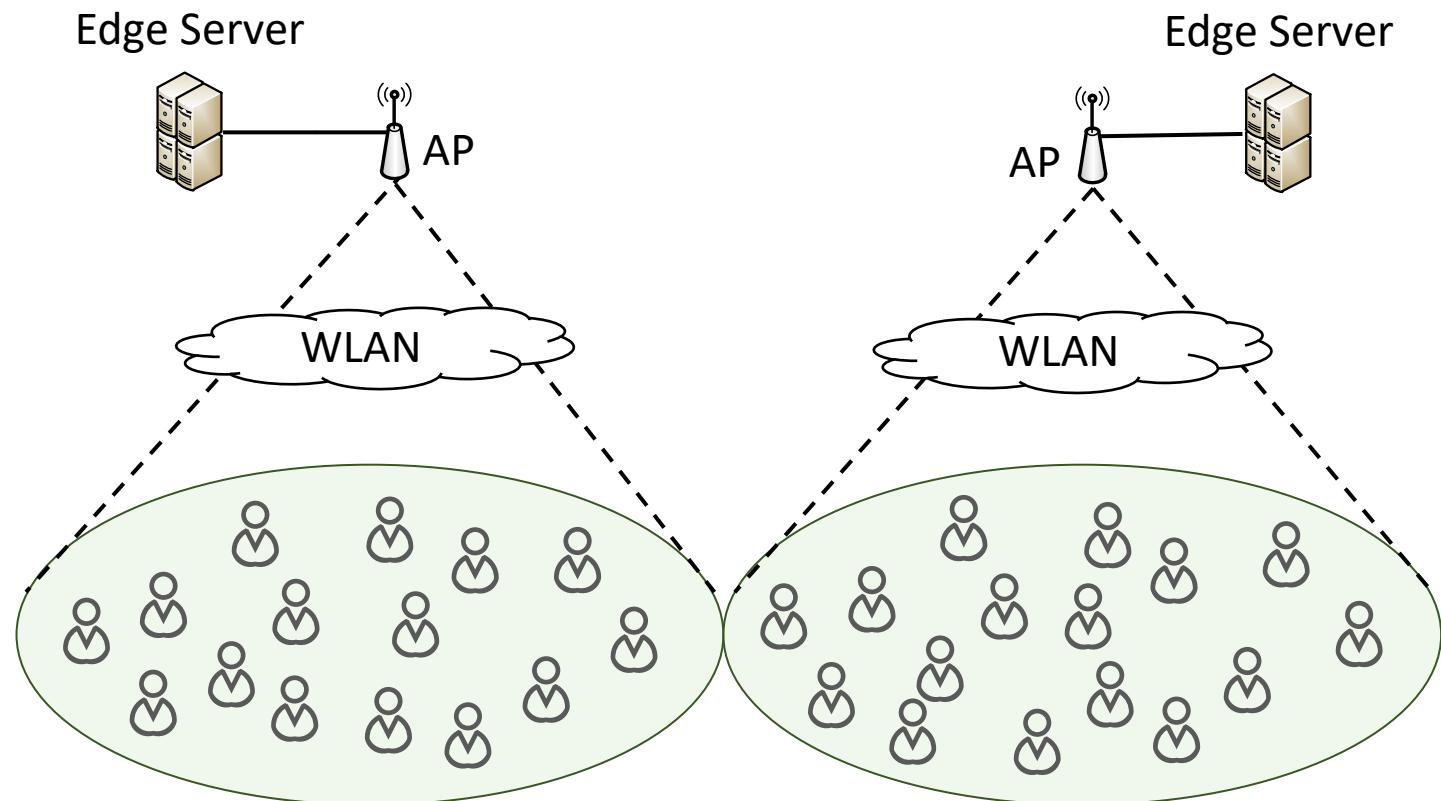
Performance Evaluation of Different VM Allocation Policies

Find the source code below:

[https://github.com/CagataySonmez/PerformanceEvaluationWithEdgeCloudSim  
/tree/main/src/edu/boun/edgecloudsim/applications/scenario1](https://github.com/CagataySonmez/PerformanceEvaluationWithEdgeCloudSim/tree/main/src/edu/boun/edgecloudsim/applications/scenario1)

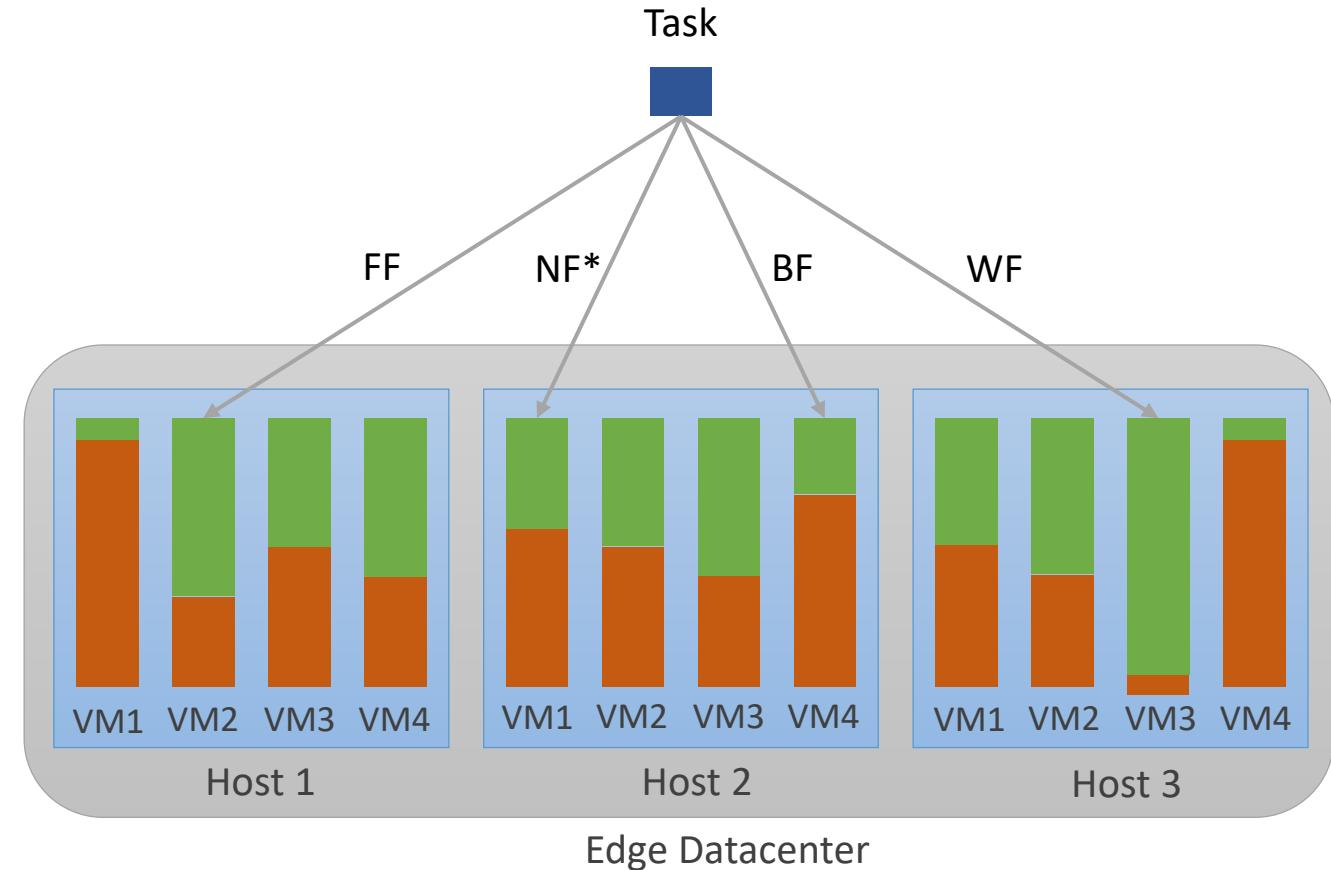
# Simulation Scenario

- Mobile devices can only offload task to the edge servers connected to the serving access point
- Edge servers operates a variable number of VMs
- This scenario compares different VM provisioning algorithms



# Competitor VM Provisioning Algorithms

- **Random (RND)**: A random VM is selected
- **First-Fit (FF)**: First available VM is selected
- **Next-Fit (NF)**: The hosts are visited in order and the first suitable VM is selected.
- **Best-Fit (BF)**: The VM with the highest CPU utilization is selected
- **Worst-Fit (WF)**: The VM with the least CPU utilization is selected



\* Assuming the previous selection of the NF algorithm was one of the VM in Host1.

# Applications Used in This Simulation

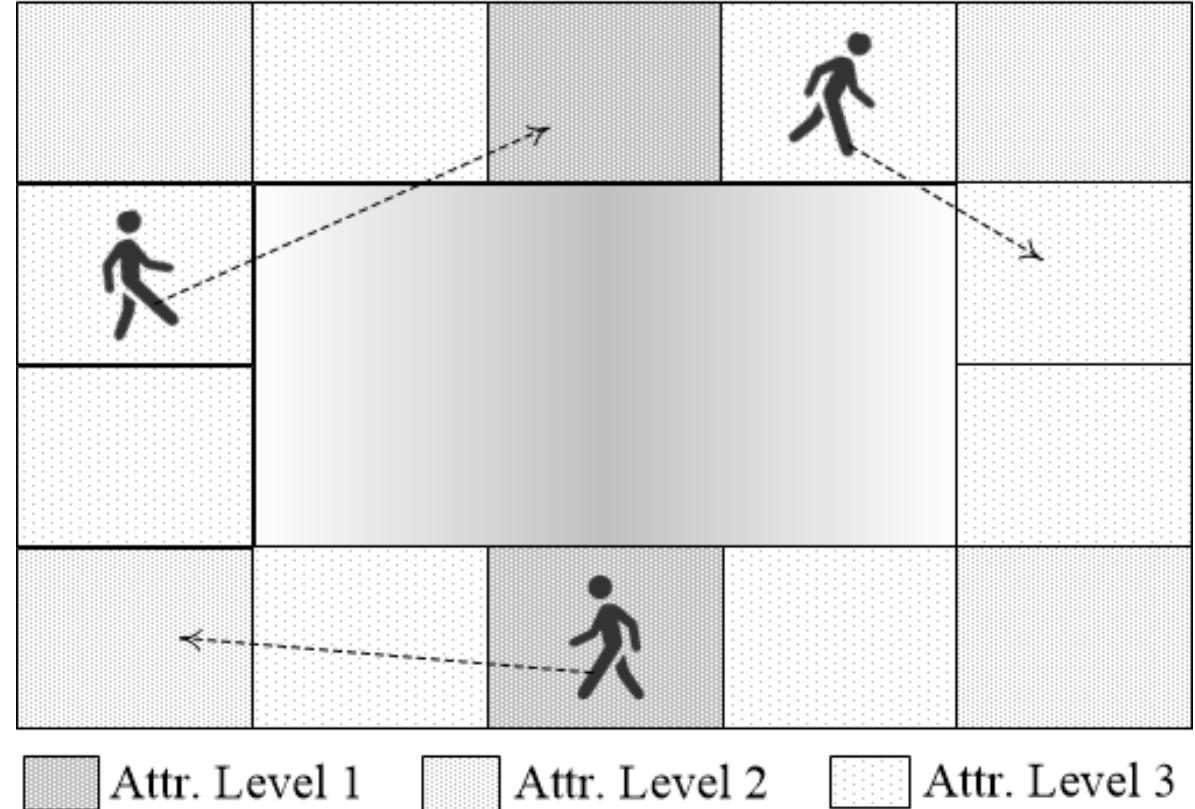
Parameter	Aug. Reality	Health	Infotainment
Usage Percentage (%)	30	20	50
Task Interarrival (sec)	2	3	7
Active/Idle Period (sec)	40/20	45/90	30/45
VM Utilization on Edge Server (%)	6	2	3.
Task Length (GI)	15	3	9
Upload/Download Data (KB)	1500/50	50/1250	250/1000



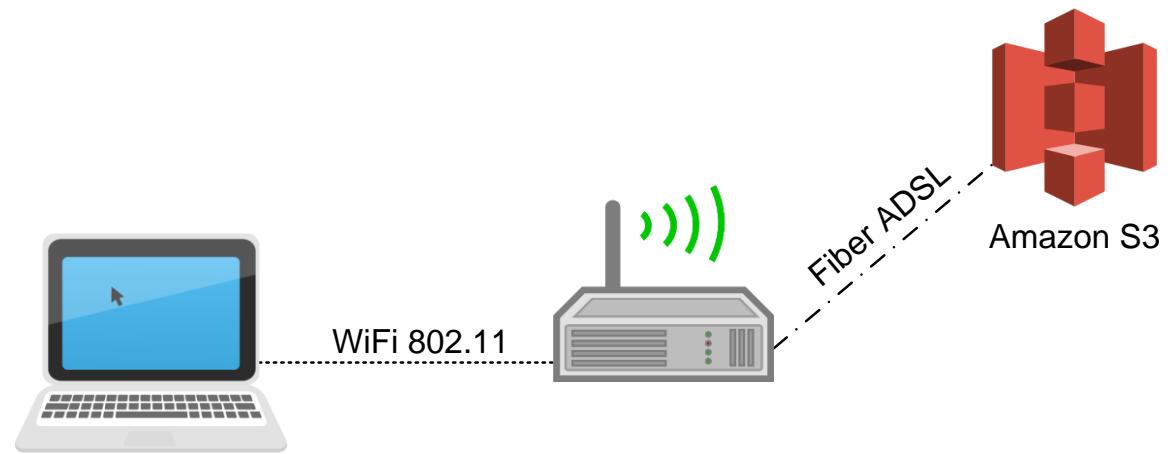
Clients are utilizing an application that generates task according to a Poisson process

# Nomadic Mobility Model

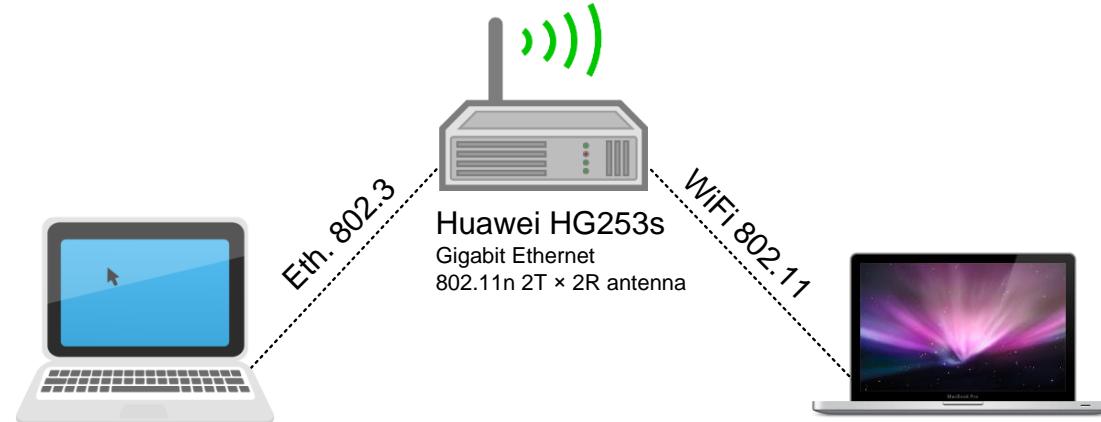
- There is no real time walking pattern, user location is updated at random time intervals
- Probability of selecting a new location is same for all locations
- We use variable locations with different attractiveness levels in simulations
- The attractiveness level determines how much time the user will spend (dwell time) in the corresponding place



# Empirical WAN/WLAN Model



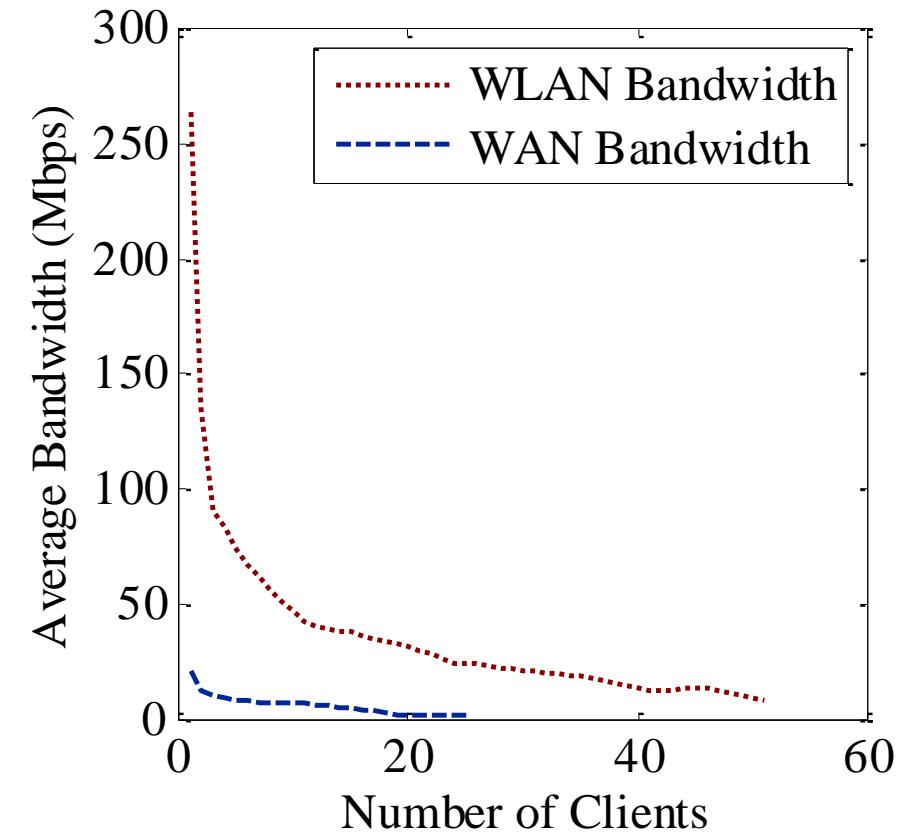
WAN Bandwidth Analysis Setup



Lenovo T550  
Intel Core i7-5600U (2.6 Ghz)  
Gigabit Ethernet  
16 GB RAM

MacBook Pro Late 2011  
Intel Core i7-2675QM (2.2 Ghz)  
802.11n WiFi  
8 GB RAM

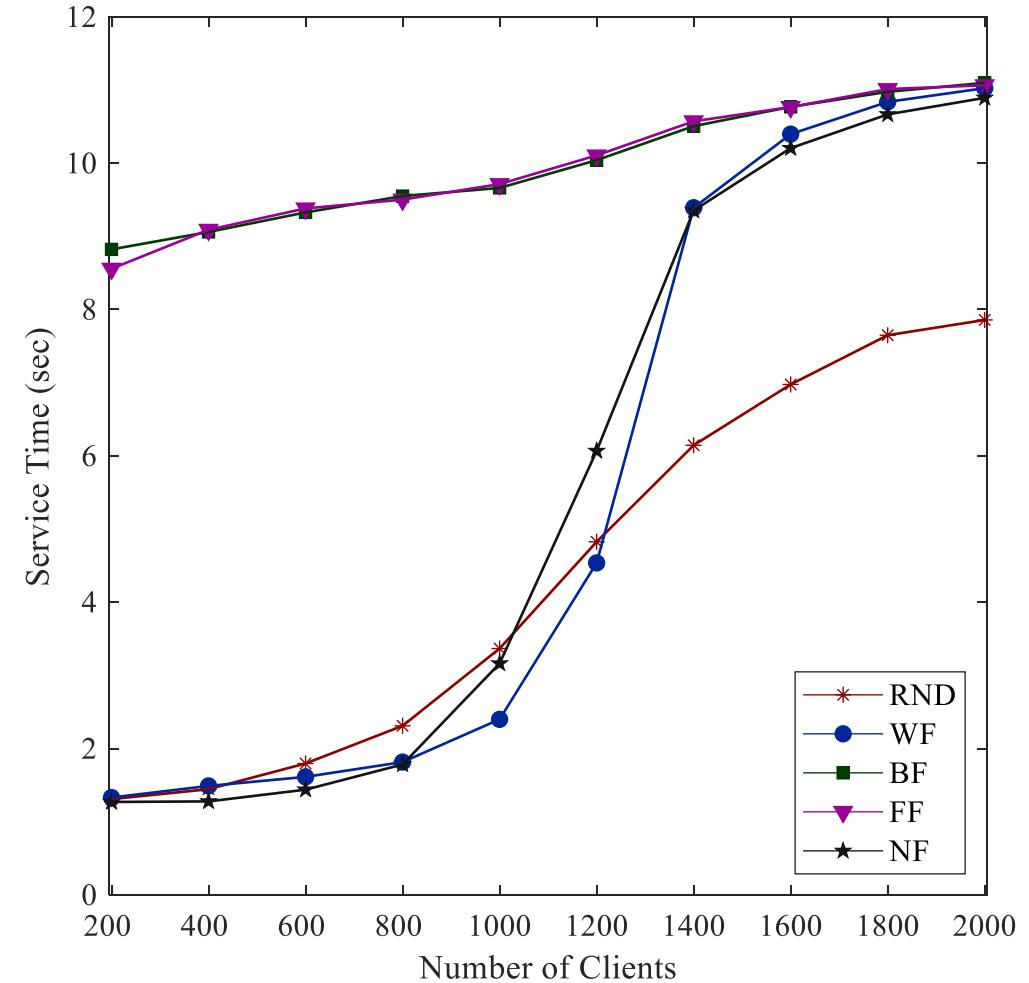
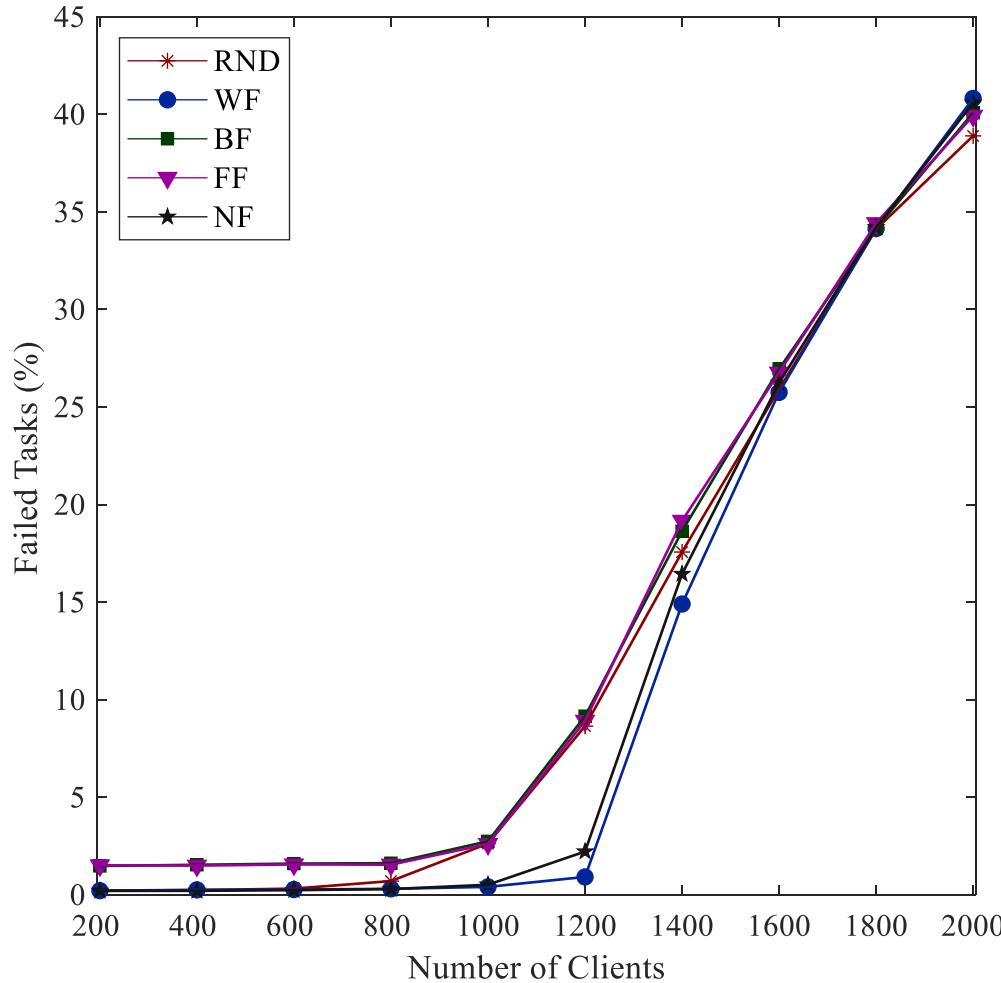
WLAN Bandwidth Analysis Setup



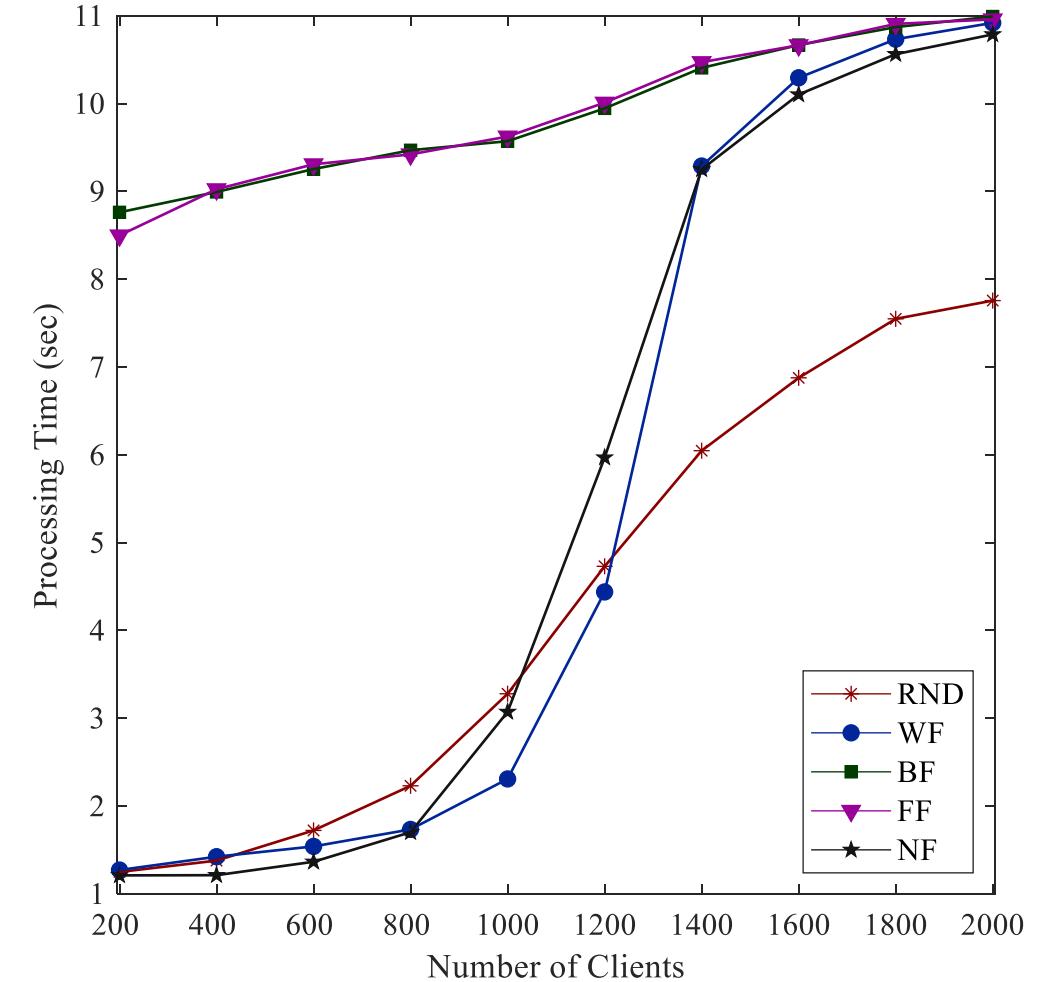
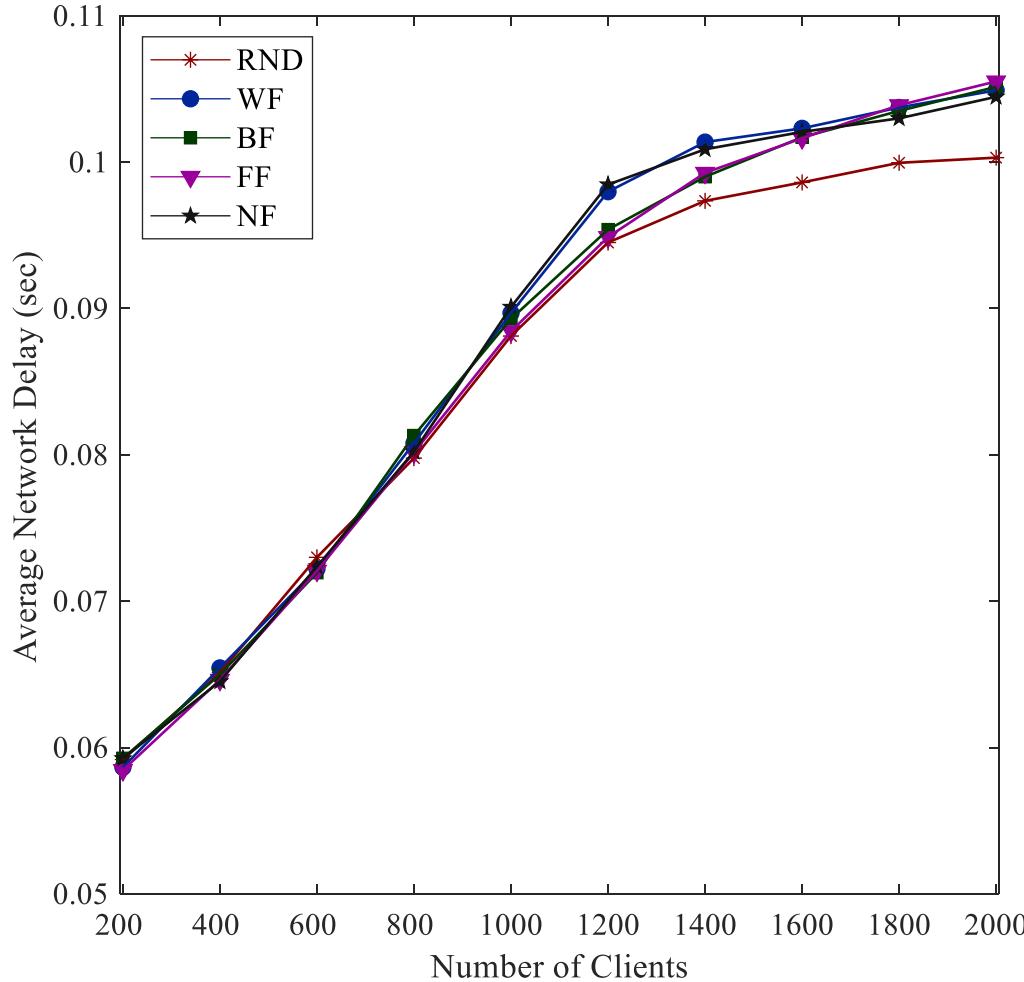
# Simulation Parameters

Parameter	Value
Simulation Time/Warm-up Period	15/1 minutes
Number of Repetition	10
WLAN Delay Model	Empirical
MAN Delay	Fixed (5 ms)
Number of VM per Edge Host	8
Number of Cores per Edge VM CPU	2
VM Processor Speed per Edge	10 GIPS
Mobility Model	Nomadic Mobility
Number of Locations for Type 1/2/3 places	2/4/8
Mean waiting time in Type 1/2/3 places	10/10/10 minutes

# Important Simulation Results

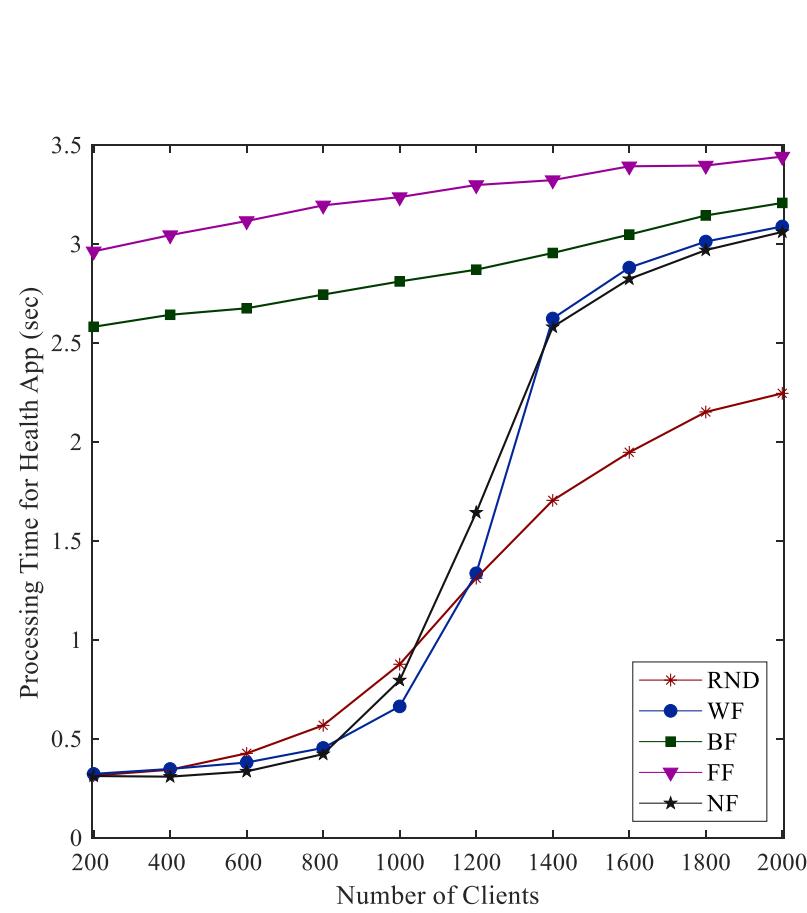


# Service Time Analysis

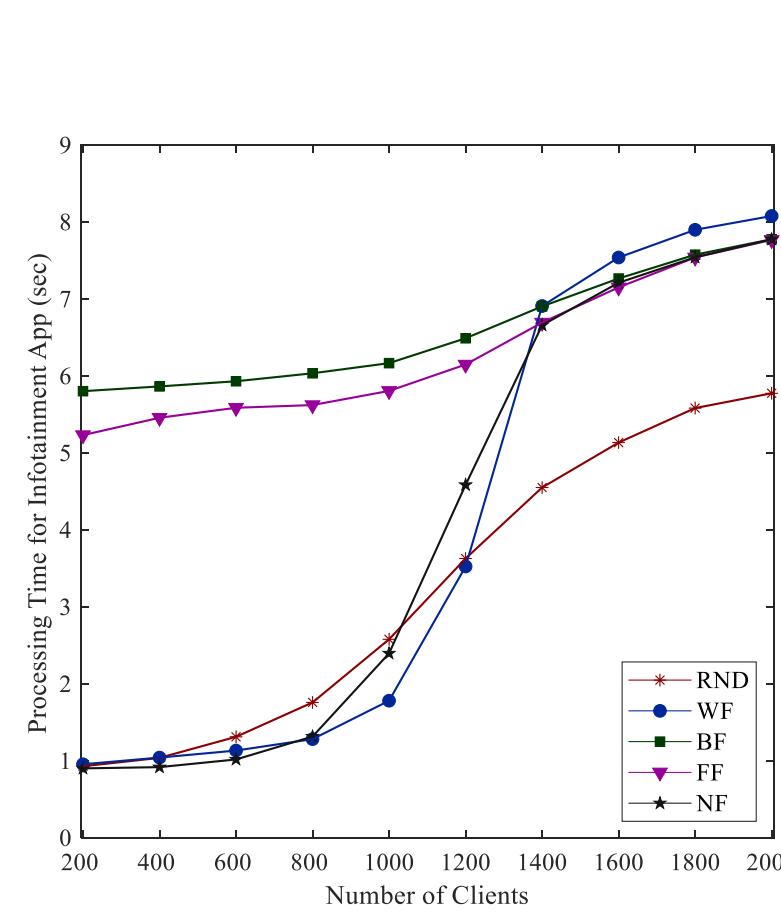


Processing time dominates the average service time

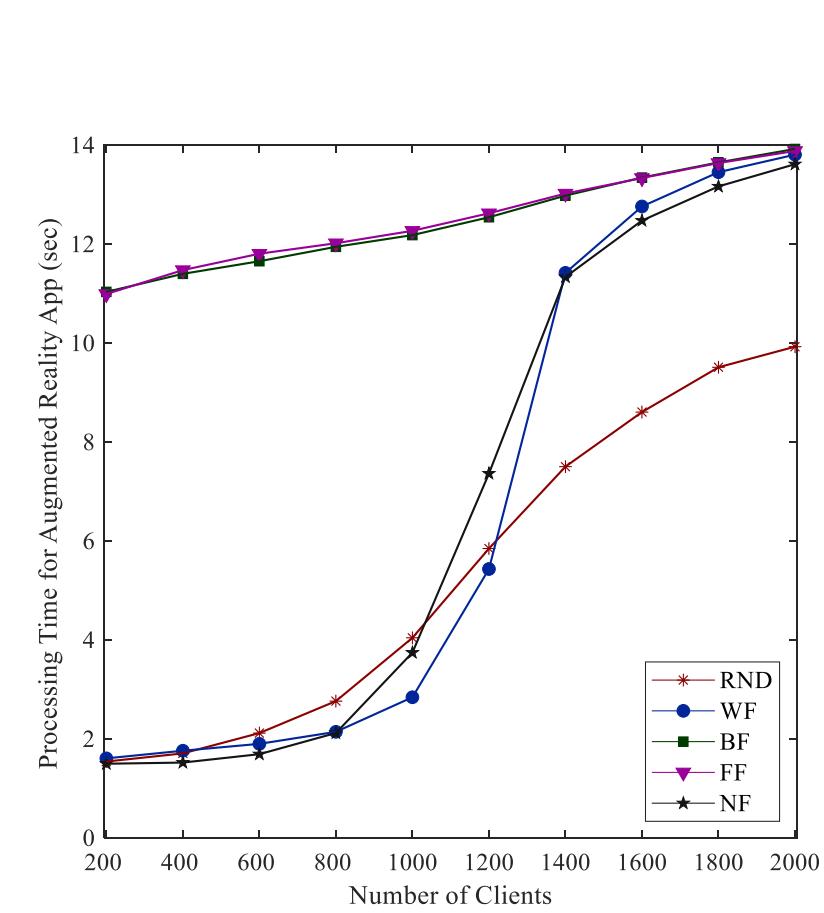
# Processing Time per Task Types



Task Size: 3 GI



Task Size: 9 GI



Task Size: 15 GI



## Case Study 2 – What to Offload

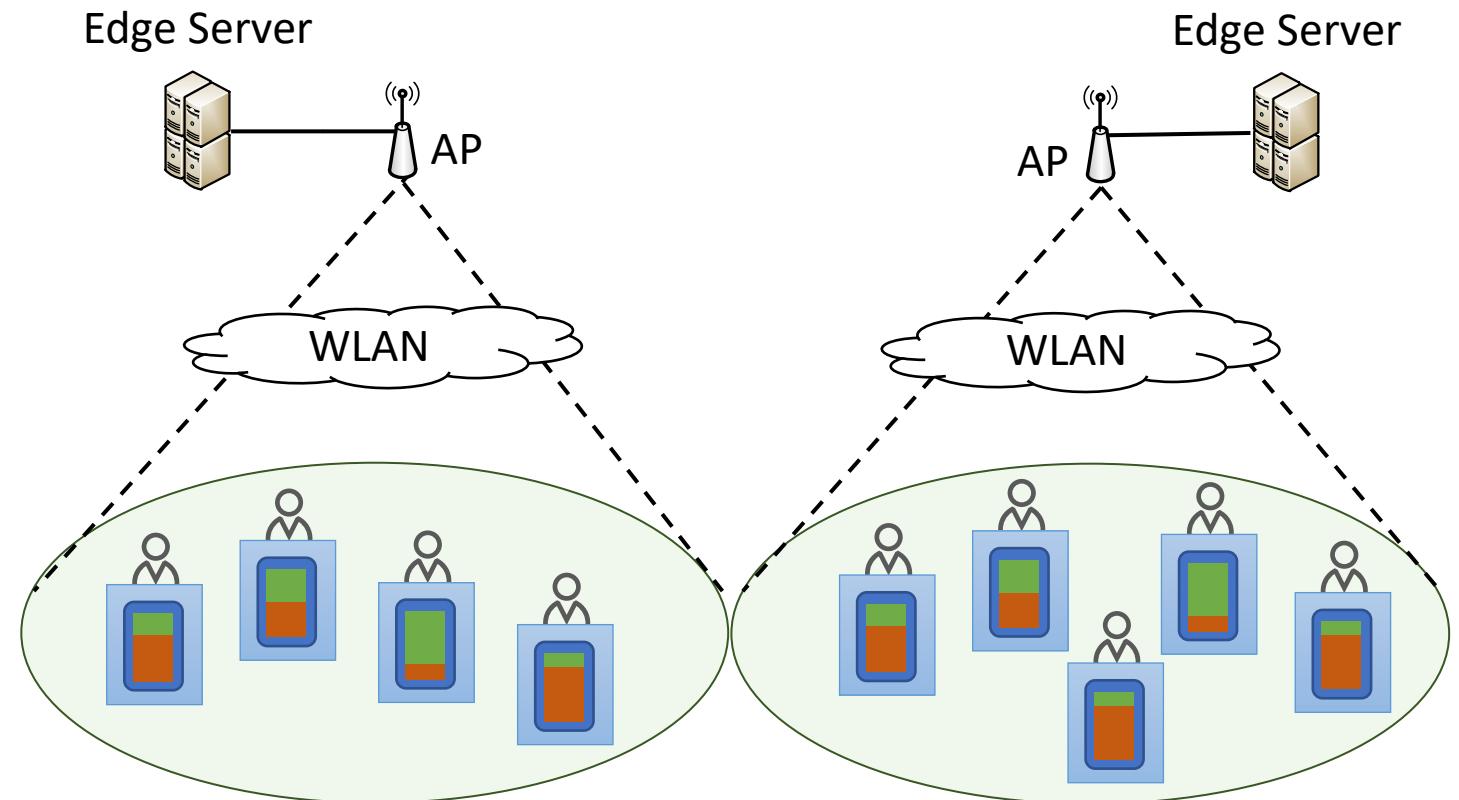
Performance Evaluation of Different Approaches that Decide Granularity of Task Offloading

Find the source code below:

[https://github.com/CagataySonmez/PerformanceEvaluationWithEdgeCloudSim  
/tree/main/src/edu/boun/edgecloudsim/applications/scenario2](https://github.com/CagataySonmez/PerformanceEvaluationWithEdgeCloudSim/tree/main/src/edu/boun/edgecloudsim/applications/scenario2)

# Simulation Scenario

- Mobile devices can operate tasks locally or offload them to the edge servers connected to the serving access point
- Edge servers operates a variable number of VMs
- Worst-fit VM provisioning (least loaded first) algorithm is used



# Competitor Task Offloading Algorithms

- **Random:** A random VM is selected
- **Mobile Device Utilization Heuristic**

If average mobile device CPU utilization < 75 execute task locally  
Otherwise, offload to edge server

- **Edge Utilization Heuristic**

If average edge server CPU utilization < 90 offload task to edge server  
Otherwise, execute task locally

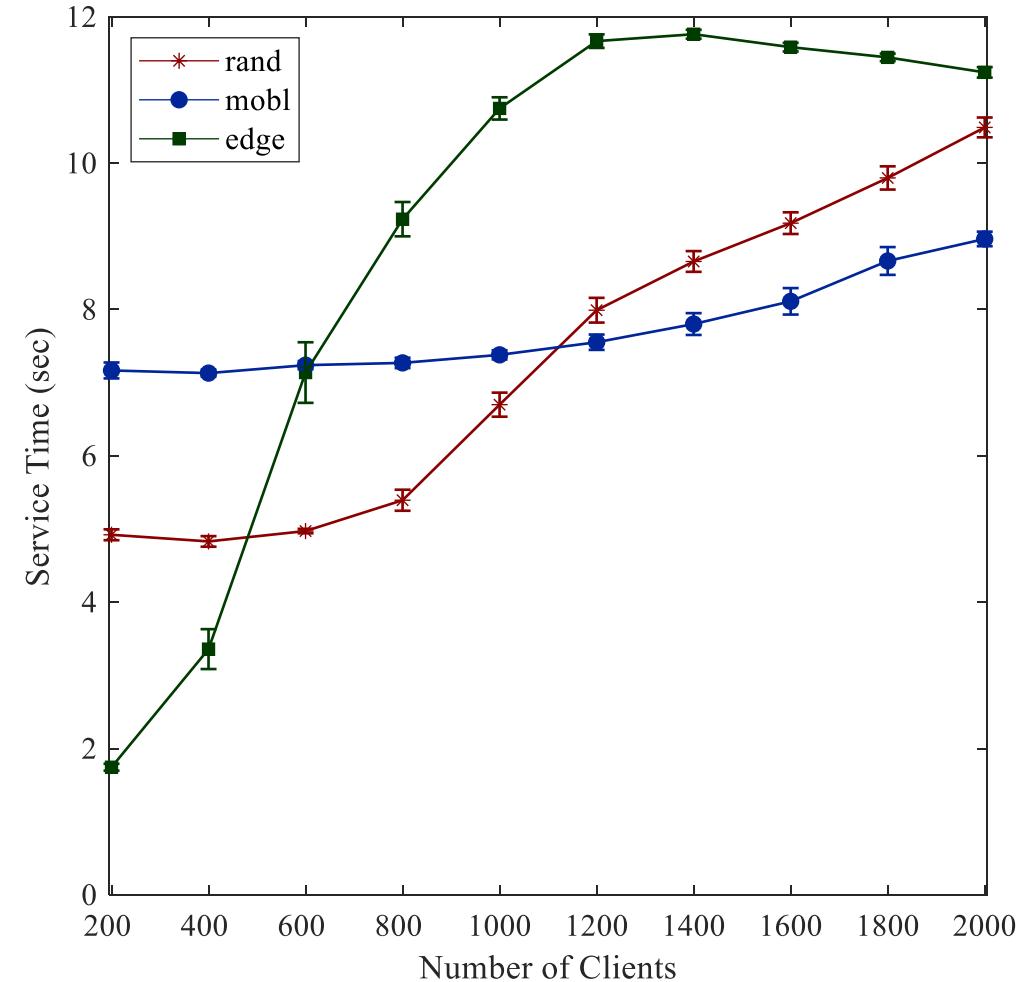
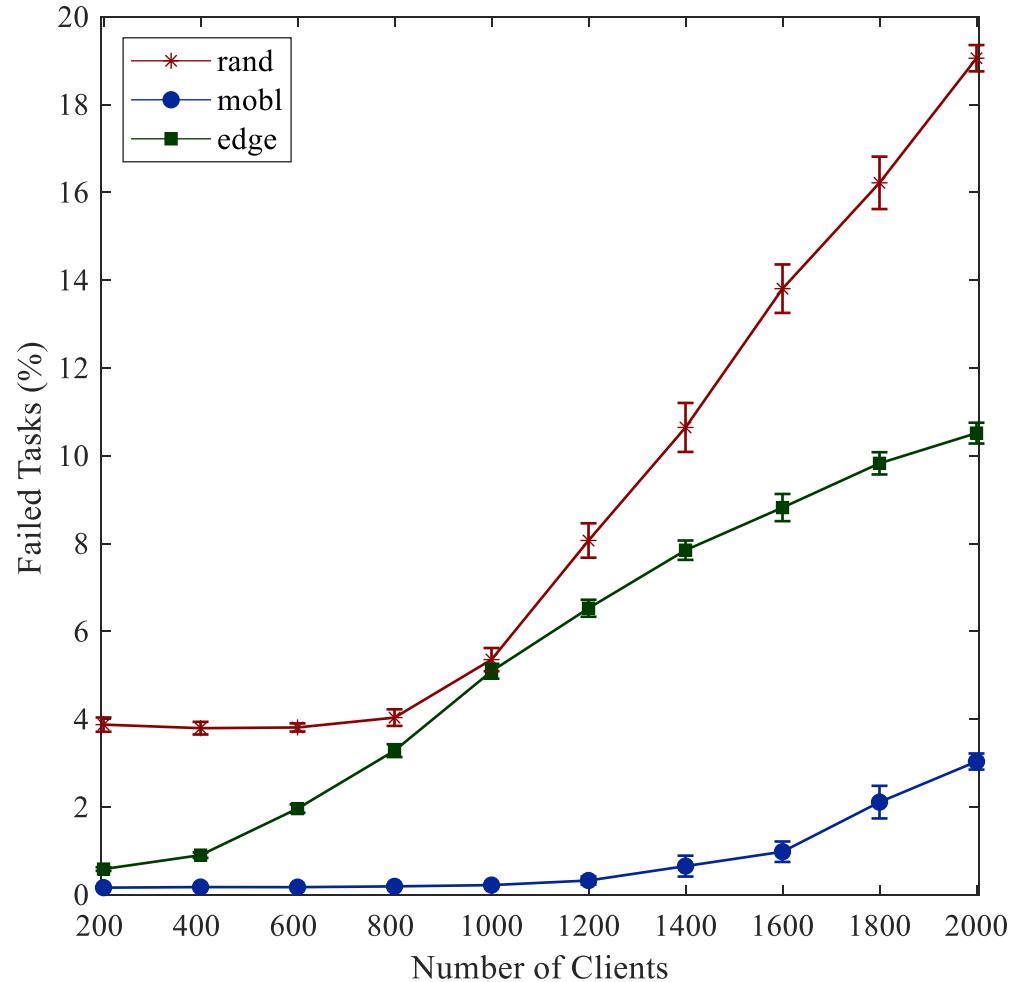
# Applications Used in This Simulation

Parameter	Aug. Reality	Health	Infotainment
Usage Percentage (%)	30	30	40
Task Interarrival (sec)	2	3	5
Active/Idle Period (sec)	40/20	60/30	30/30
VM Utilization on Edge/Client (%)	5/20	2/8	4/1
Task Length (GI)	20	8	16
Upload/Download Data (KB)	3000/1000	900/500	2000/4000

# Simulation Parameters

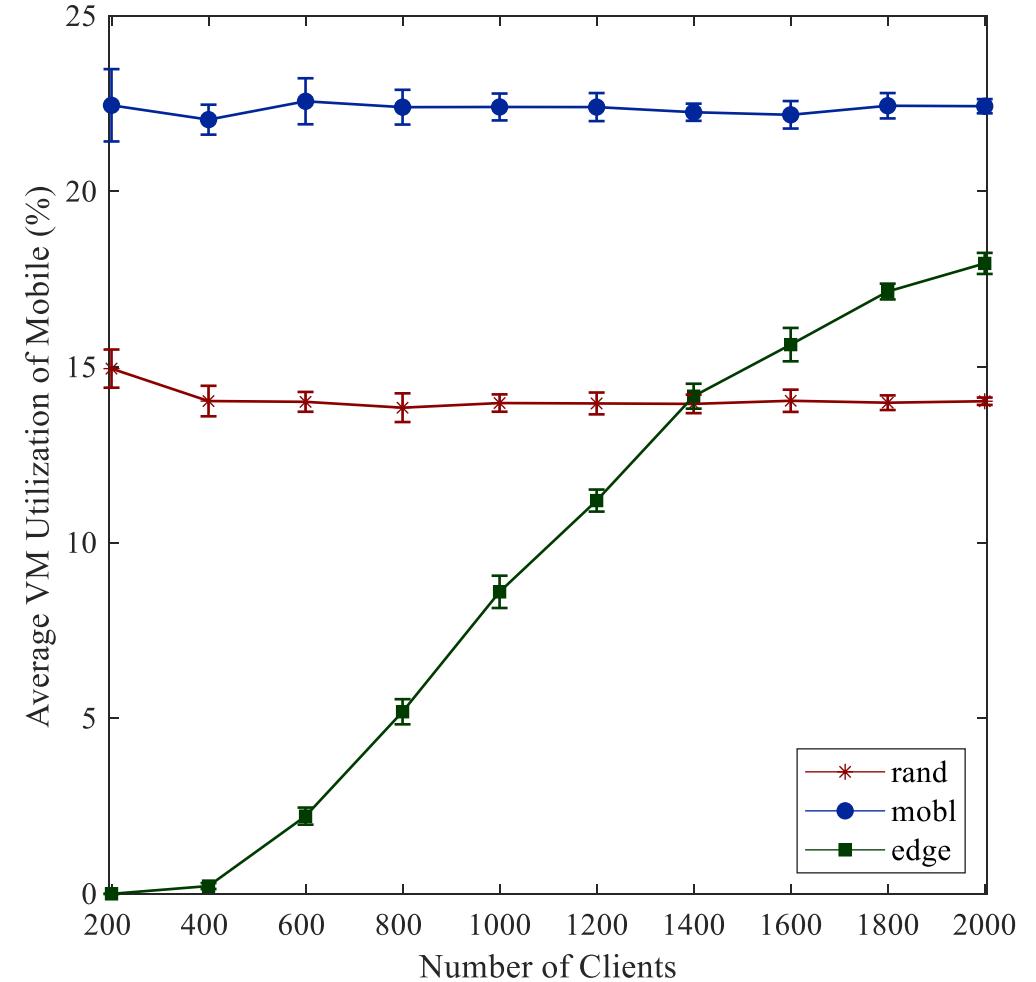
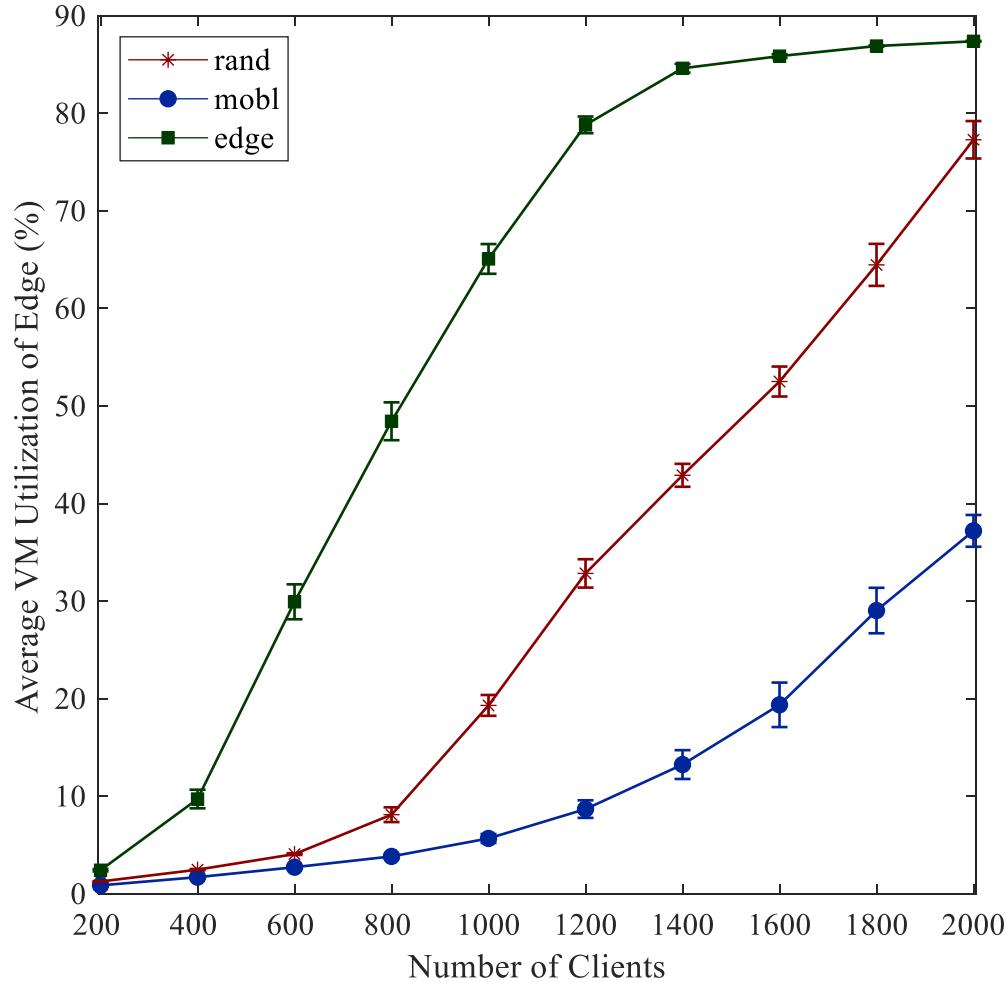
Parameter	Value
Simulation Time/Warm-up Period	15/1 minutes
Number of repetition	10
WLAN Delay Model	Empirical
MAN Delay	Fixed (5 ms)
Number of VM per Edge/Client Host	8/1
Number of Cores per Edge/Client VM CPU	2/1
VM Processor Speed per Edge/Client	10/4 GIPS
Mobility Model	Nomadic Mobility
Number of locations for Type 1/2/3 places	2/4/8
Mean waiting time in Type 1/2/3 places	10/6.6/3.3 minutes

# Important Simulation Results

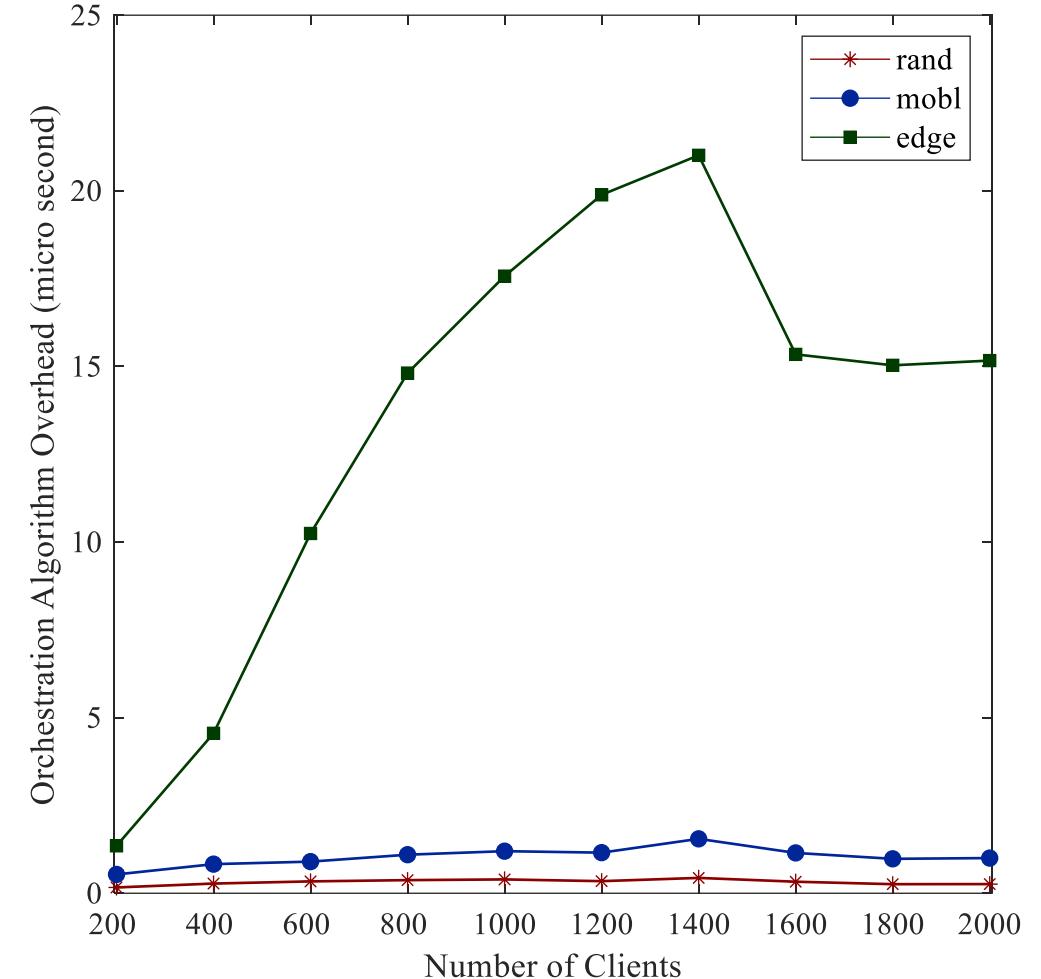
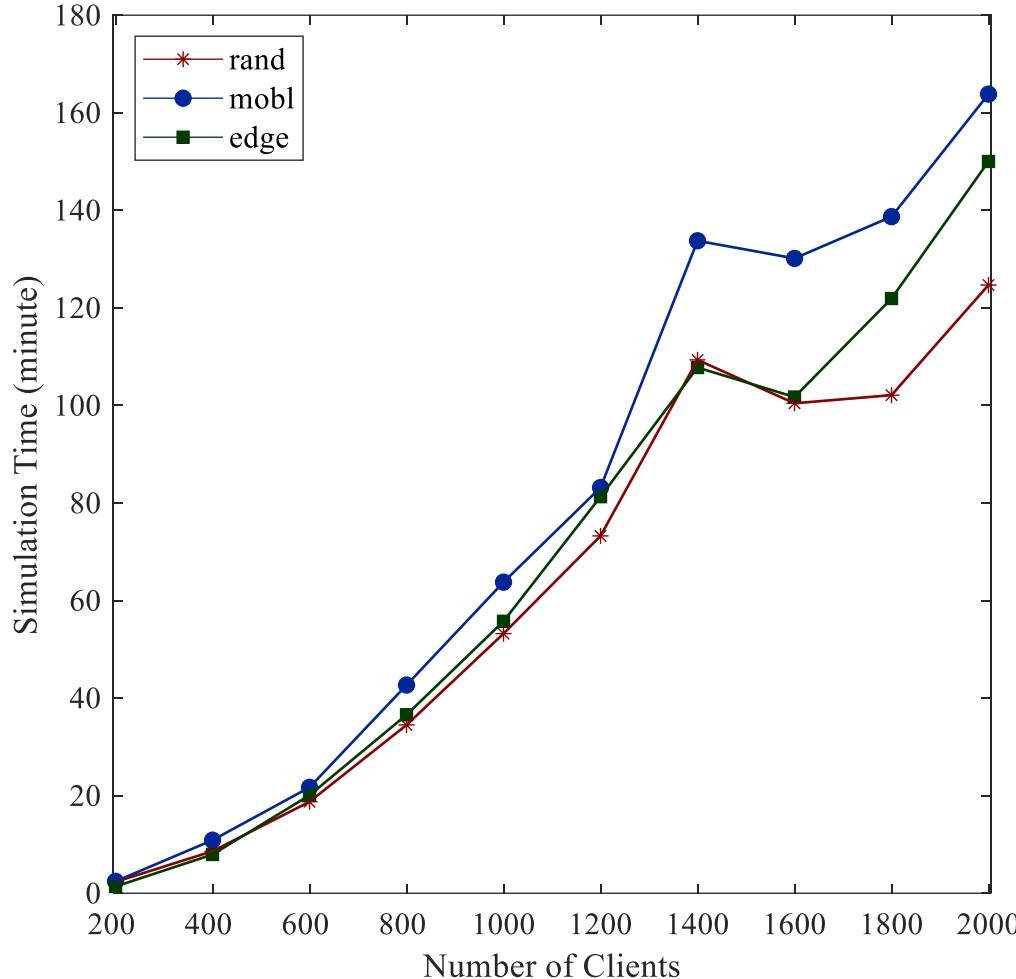


Graph is plotted with 95% confidence interval error bars

# VM Utilization Analysis



# Complexity Analysis



★ The results are highly dependent to host machine load while running the simulation!



# Case Study 3 – Where to Offload

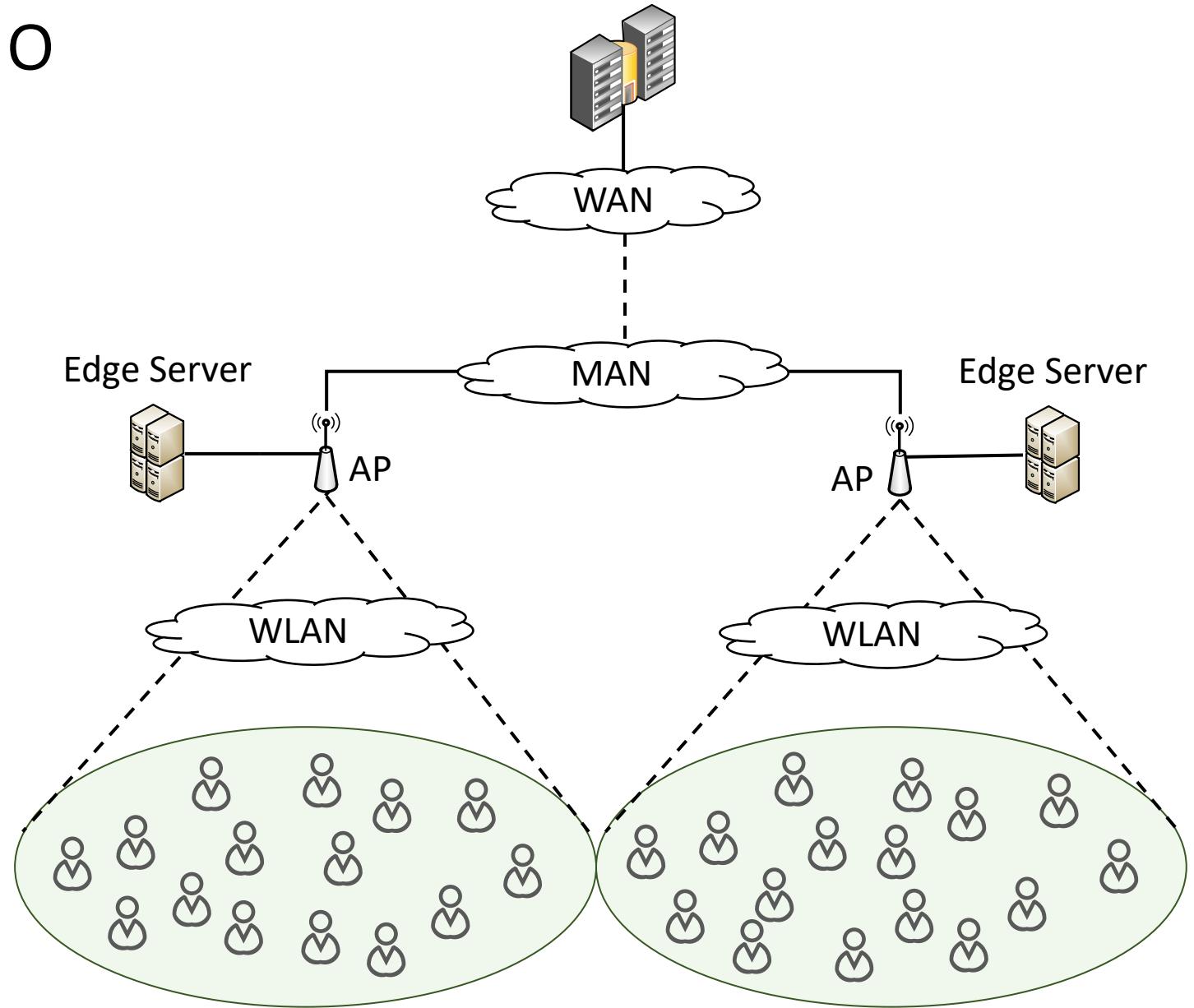
Performance Evaluation of Different Workload Orchestration Policies

Find the source code below:

[https://github.com/CagataySonmez/PerformanceEvaluationWithEdgeCloudSim  
/tree/main/src/edu/boun/edgecloudsim/applications/scenario3](https://github.com/CagataySonmez/PerformanceEvaluationWithEdgeCloudSim/tree/main/src/edu/boun/edgecloudsim/applications/scenario3)

# Simulation Scenario

- Mobile can offload tasks to edge or cloud servers
- Worst-fit VM provisioning (least loaded first) algorithm is used
- If the task is sent to another edge server outside the connected network, it is transmitted via MAN
- WLAN and WAN delays are modeled independently, so the WLAN is not affected if task is sent to remote server



# Competitor Edge Orchestration Algorithms

- **Random:** A random server is selected to offload task
- **Edge Server Utilization Heuristic**

If average edge servers CPU utilization > 75, offload task to cloud server  
Otherwise, offload task to edge servers

- **Network Utilization Heuristic**

If WAN bandwidth > 5 Mbps, offload task to cloud server  
Otherwise, offload task to edge servers

# Applications Used in This Simulation

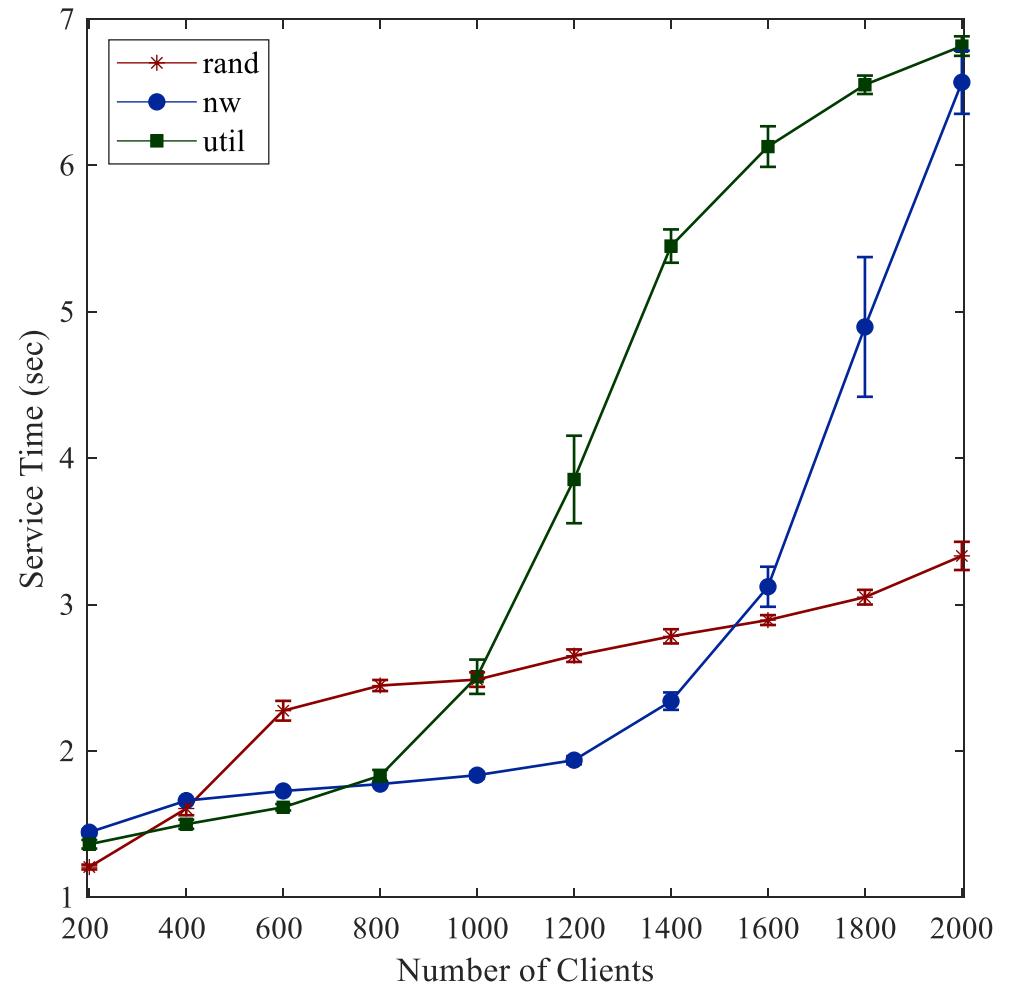
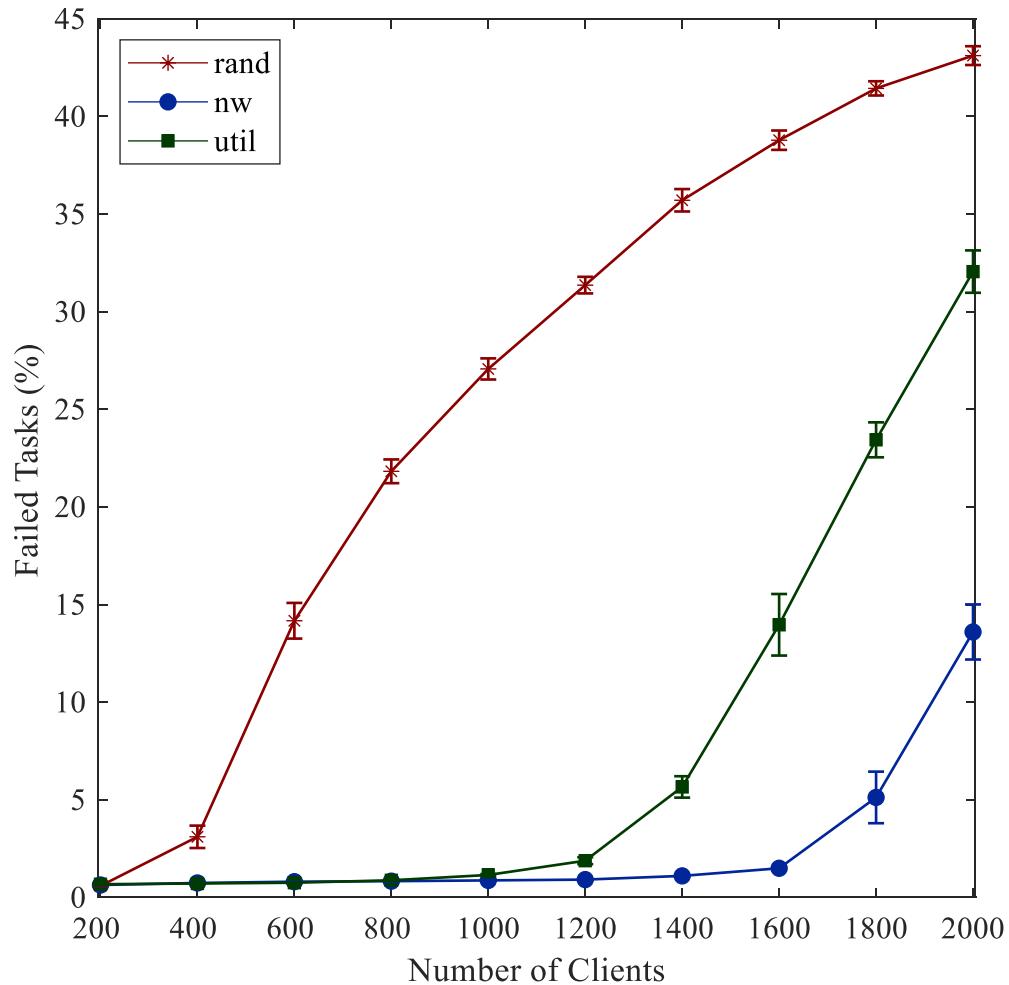
Parameter	Aug. Reality	Health	Infotainment
Usage Percentage (%)	30	20	50
Task Interarrival (sec)	2	3	7
Active/Idle Period (sec)	40/20	45/90	30/45
VM Utilization on Edge/Cloud (%)	6/0.6	2/0.2	10/1
Task Length (GI)	15	3	9
Upload/Download Data (KB)	1500/50	50/1250	250/1000

Should be 3.6/0.36; This bug is fixed in GitHub!

# Simulation Parameters

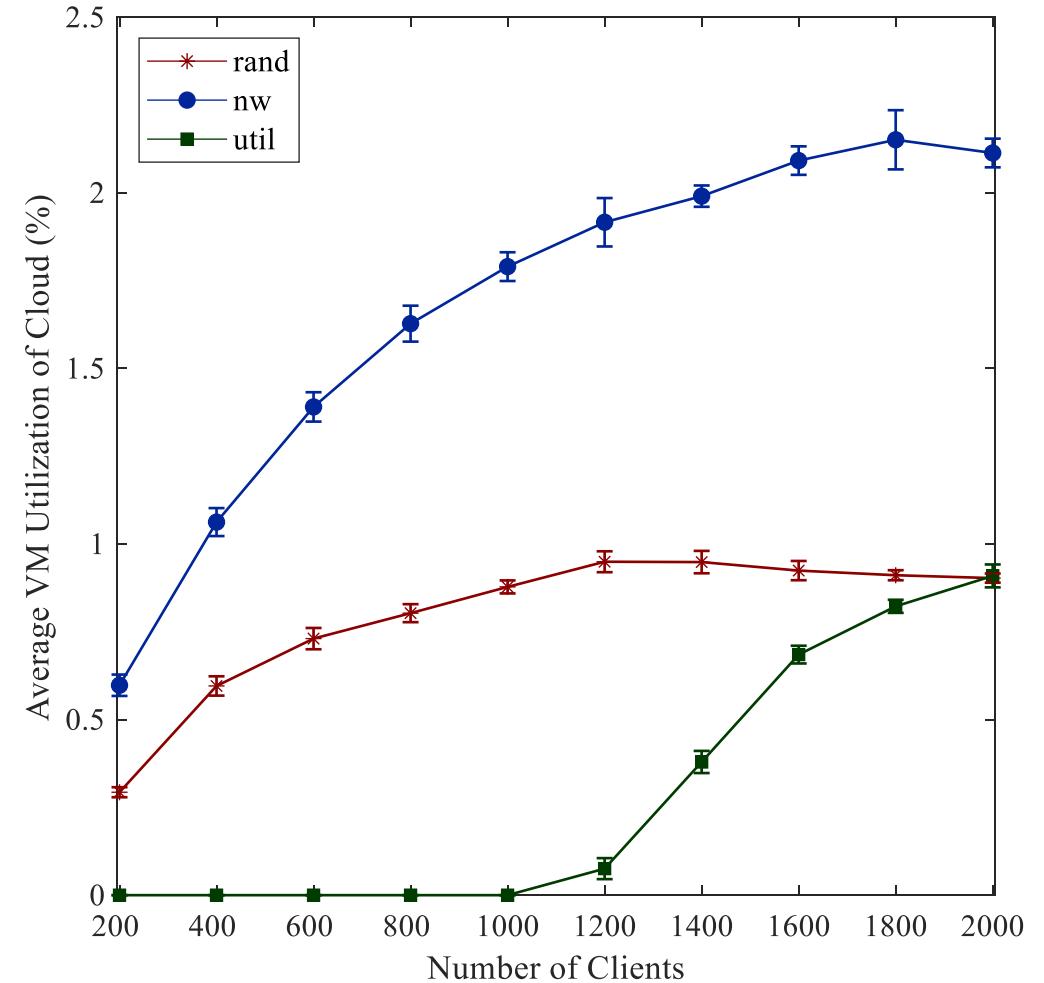
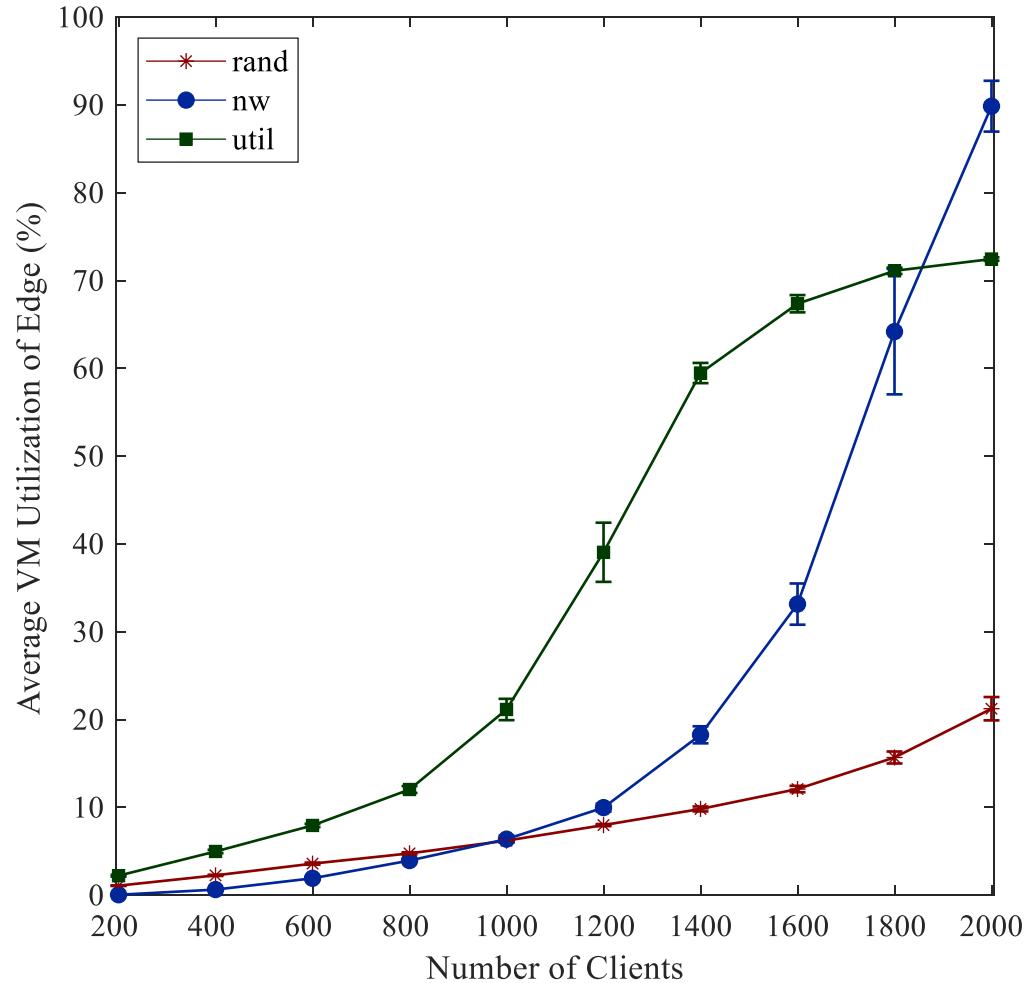
Parameter	Value
Simulation Time/Warm-up Period	15/1 minutes
Number of repetition	10
WAN/WLAN Delay Model	Empirical
MAN Delay	Fixed (5 ms)
Number of VM per Edge/Cloud Host	8/4
Number of Cores per Edge/Cloud VM CPU	2/4
VM Processor Speed per Edge/Cloud	10/100 GIPS
Mobility Model	Nomadic Mobility
Number of Locations for Type 1/2/3 Places	2/4/8
Mean waiting time in Type 1/2/3 Places	8/5/2 minutes

# Important Simulation Results



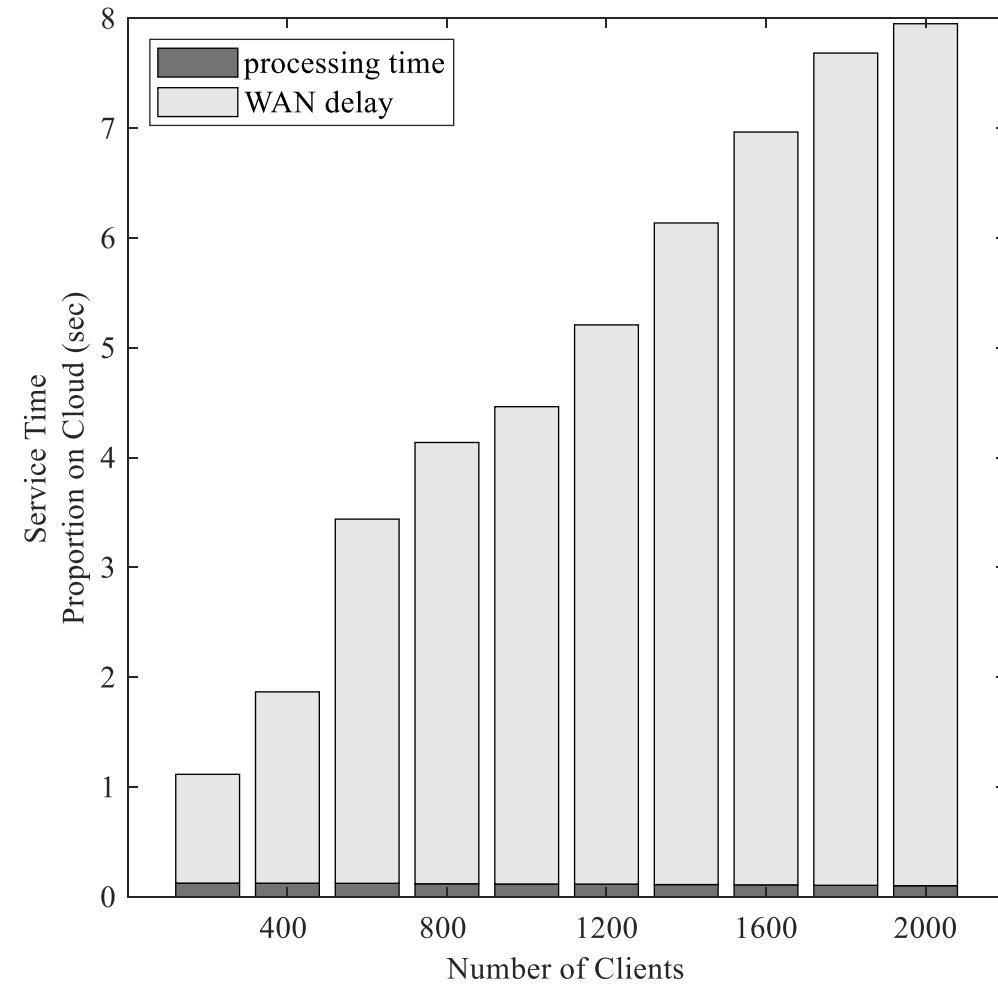
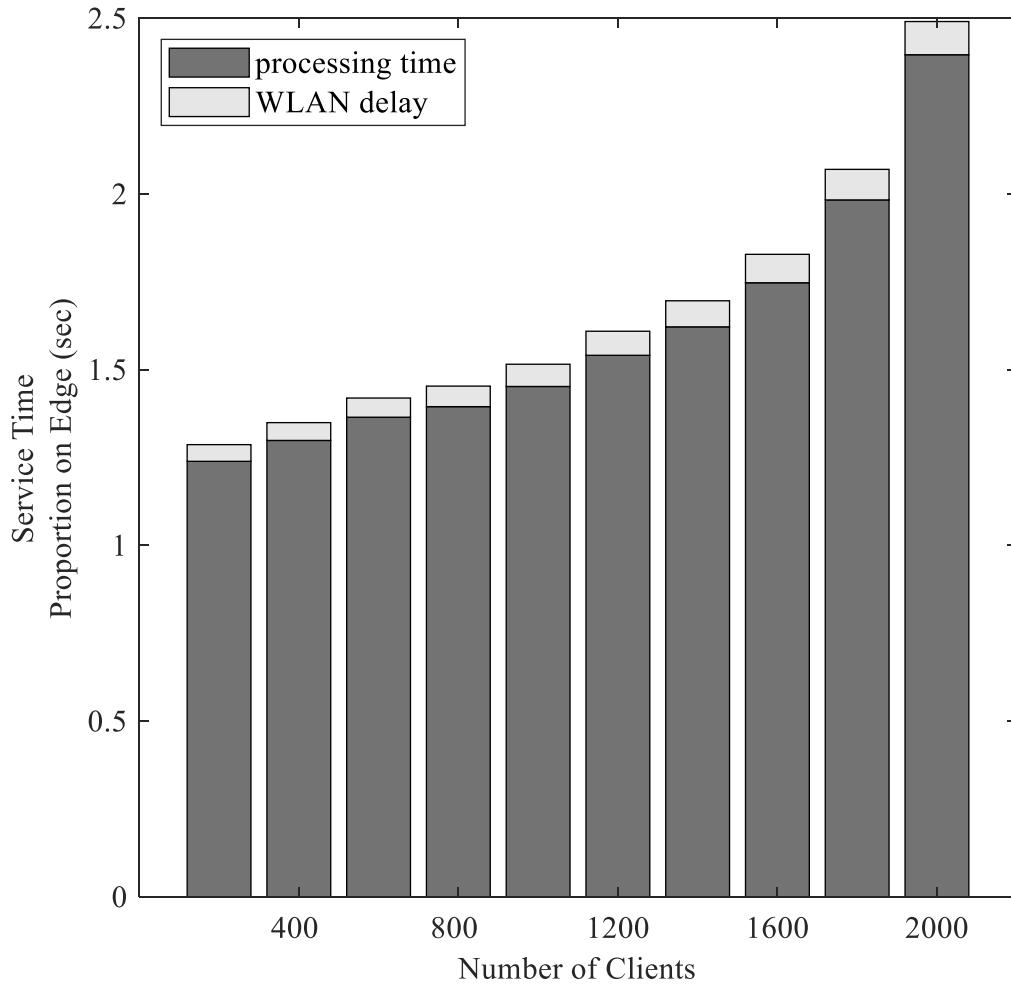
Graph is plotted with 95% confidence interval error bars

# VM Utilization Analysis



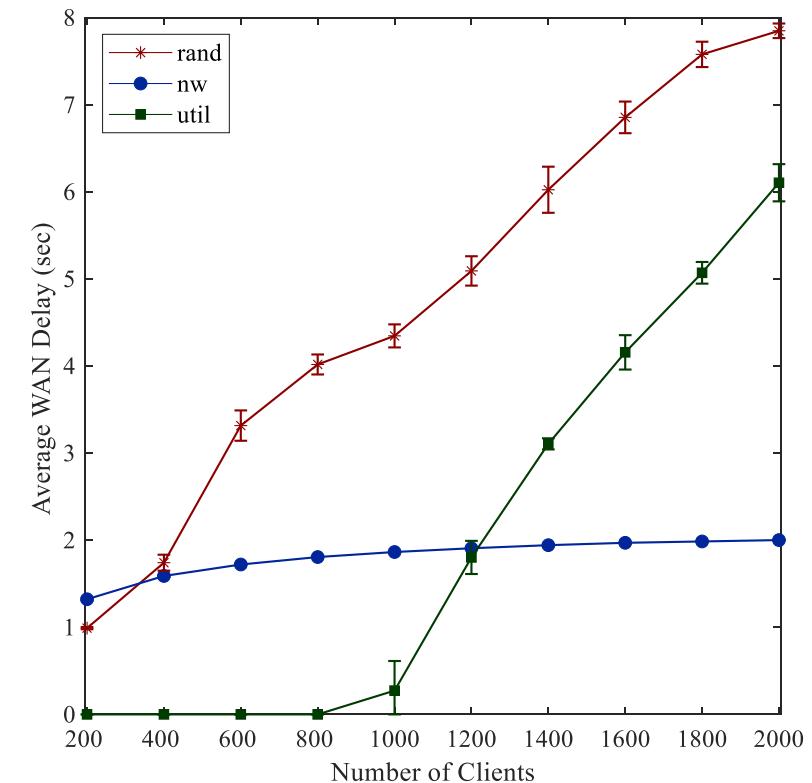
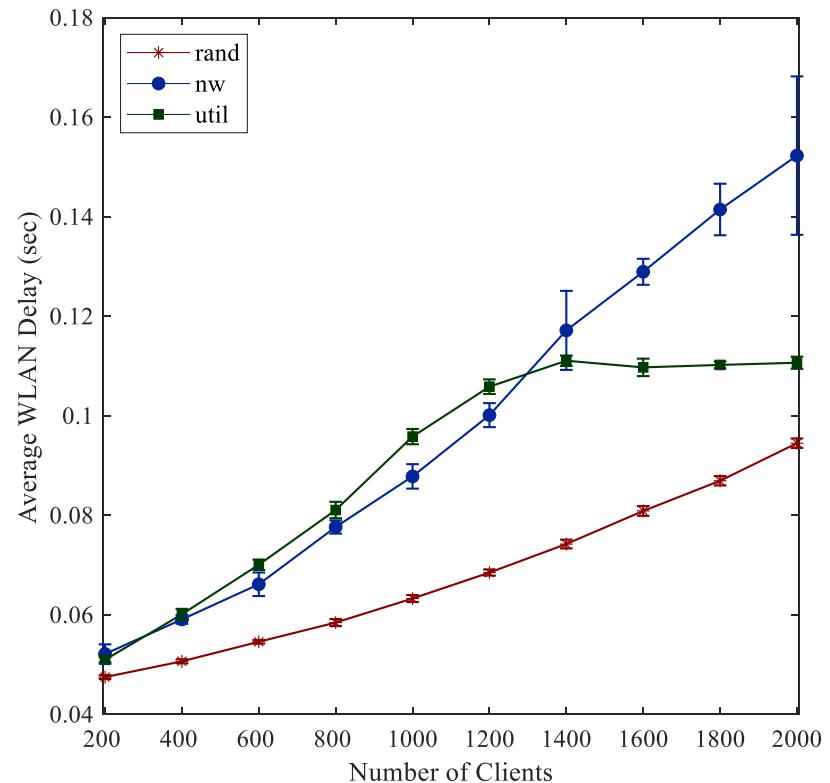
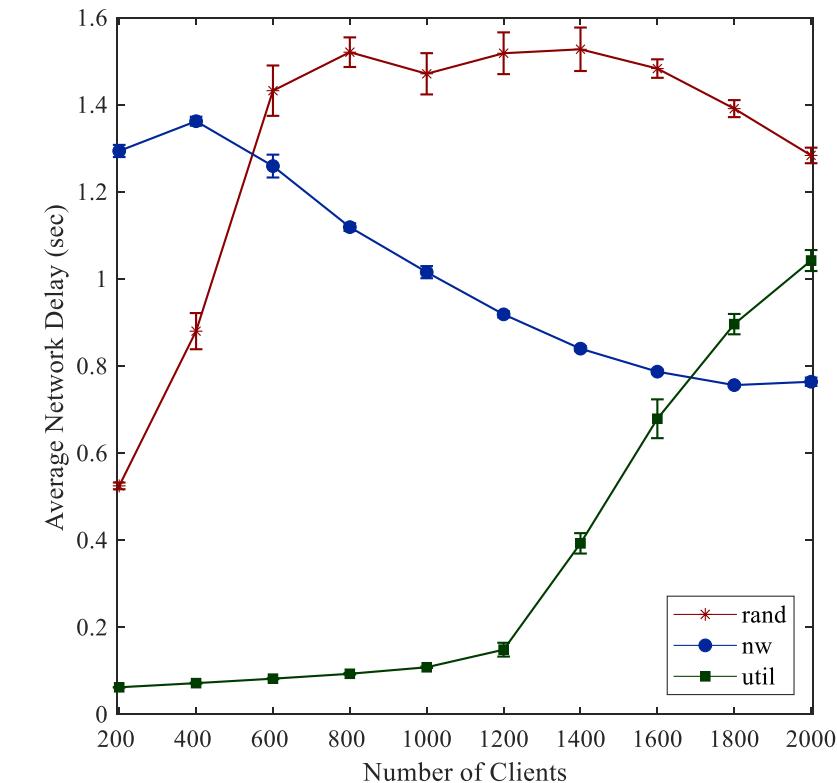
The cloud is mostly considered to be an endless pool of resources

# Service Time Analysis



★ Processing time is a problem for the Edge and WAN delay for the Cloud servers

# Network Delay Analysis



WAN delay dominates the average network delay



# Case Study 4 – Server Capacity Planning

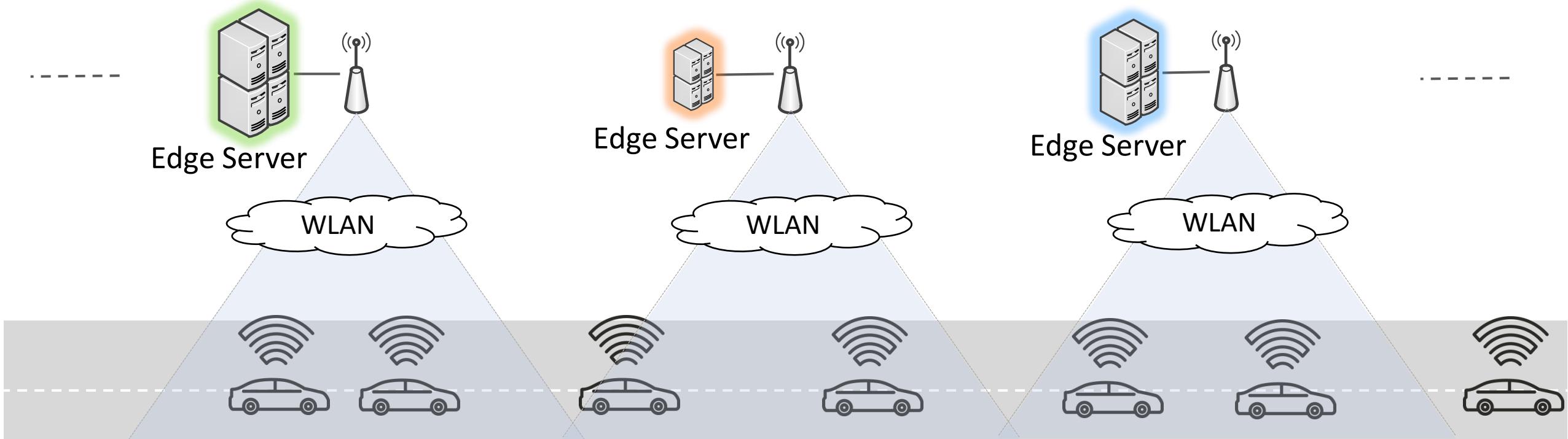
Performance Evaluation of Different Capacity Planning Approaches

Find the source code below:

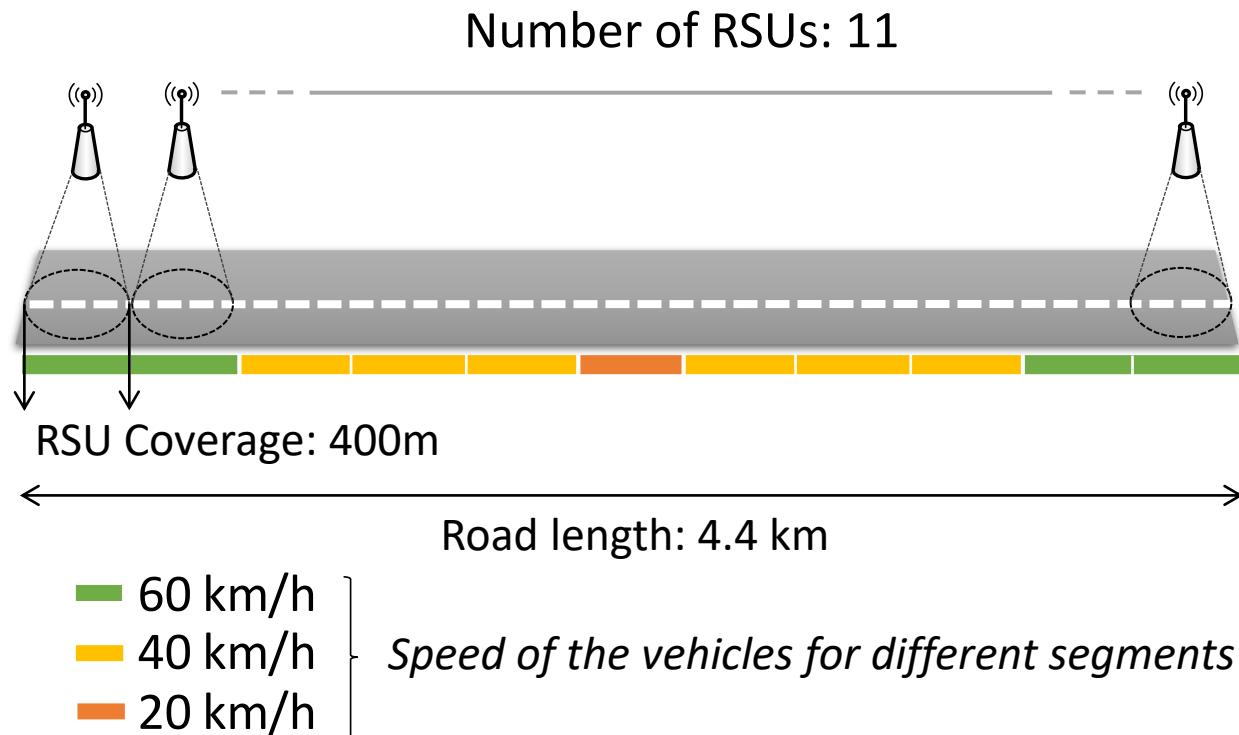
[https://github.com/CagataySonmez/PerformanceEvaluationWithEdgeCloudSim  
/tree/main/src/edu/boun/edgecloudsim/applications/scenario4](https://github.com/CagataySonmez/PerformanceEvaluationWithEdgeCloudSim/tree/main/src/edu/boun/edgecloudsim/applications/scenario4)

# Simulation Scenario

- Vehicles can only offload task to the edge servers connected to the serving access point
- Edge servers run host machines of varying capacity
- This scenario compares different edge server capacity planning algorithms



# Vehicular Mobility Model



- A **smart highway** environment is simulated
- 1000 to 2000 vehicles traveling on a circular road
- Dynamic velocity values based on the vehicle position is used

# Competitor Capacity Planning Algorithms

## ➤ RANDOM CAPACITY

- Total capacity is randomly assigned (allocated) to hosts
- Total capacity is 220 GIPS

## ➤ EQUAL CAPACITY

- Total capacity is equally distributed to the hosts
- 20 GIPS computing capacity for all hosts

## ➤ TRAFFIC DENSITY HEURISTIC

- Total capacity is distributed to the hosts in proportion to the intensity of the traffic
- 44 GIPS computing capacity for the hosts in high density areas
- 20 GIPS computing capacity for the hosts in medium density areas
- 14 GIPS computing capacity for the hosts in low density areas

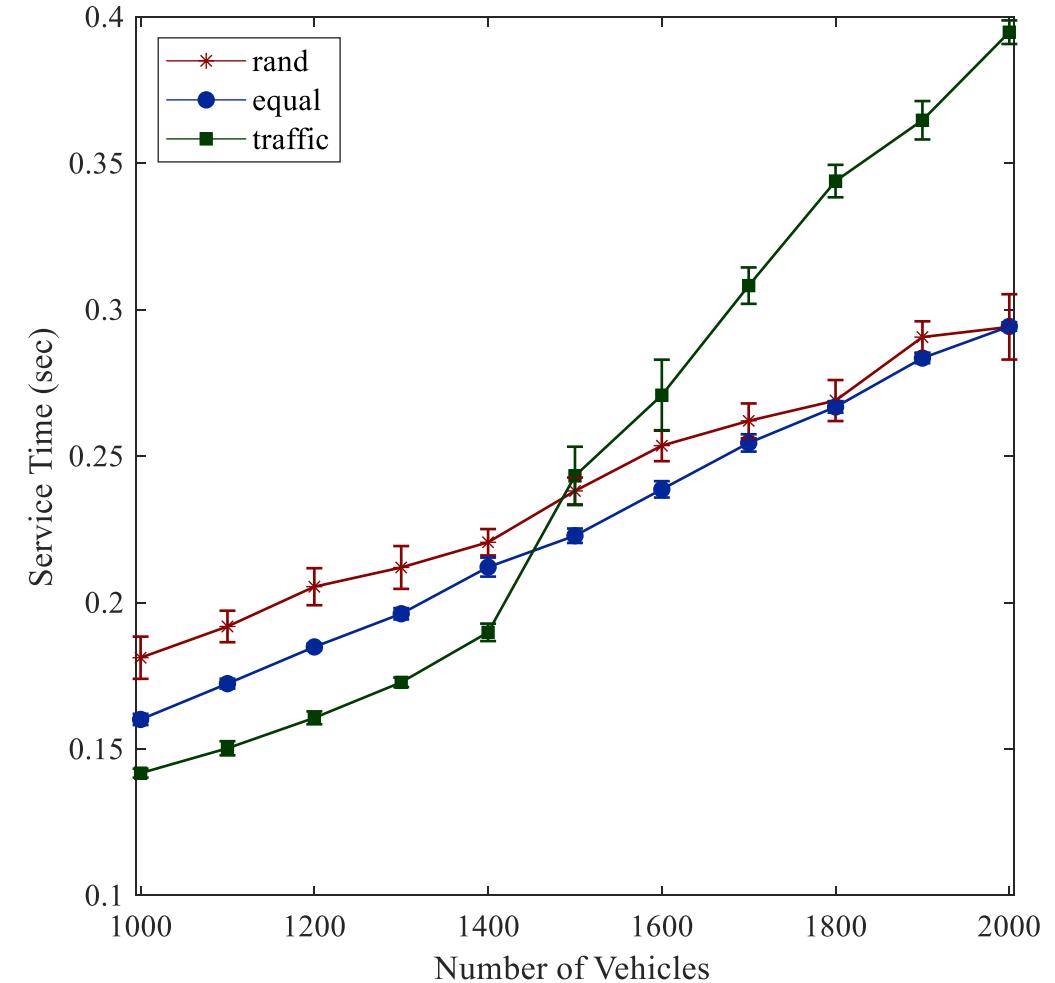
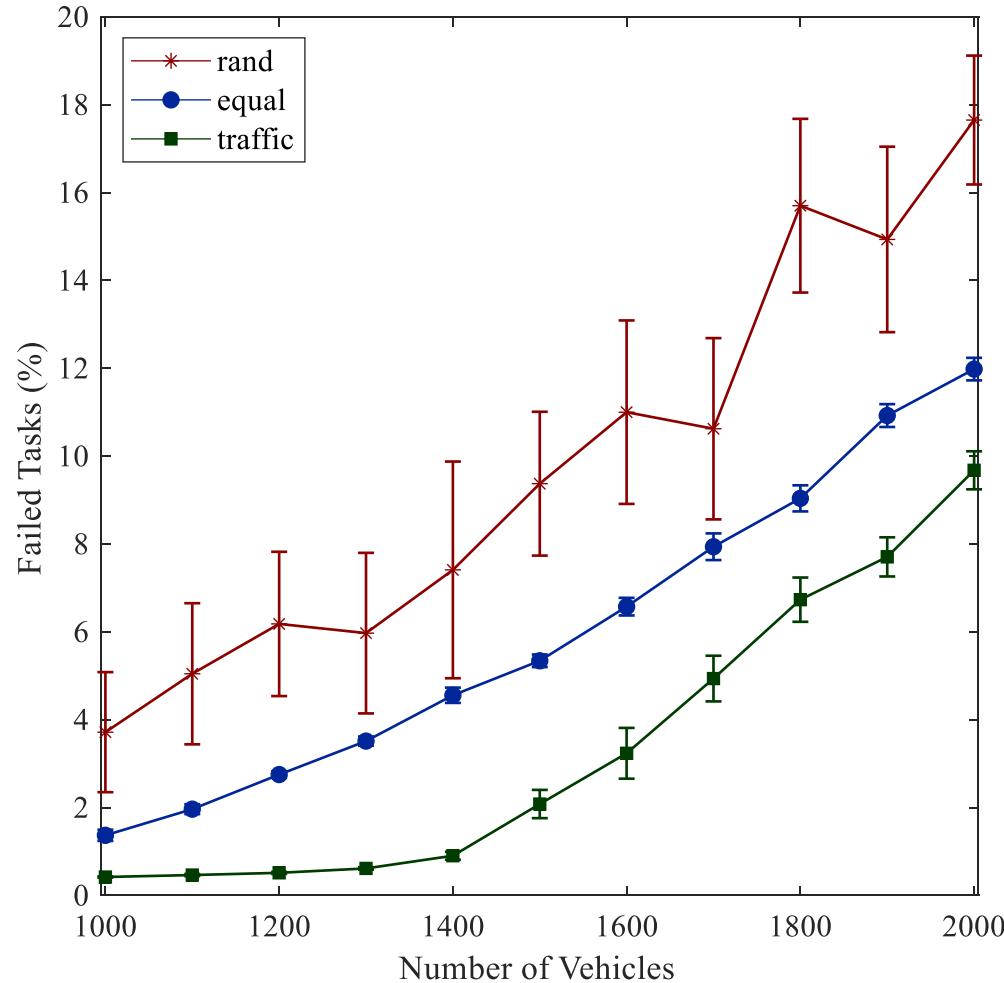
# Applications Used in This Simulations

Parameter	Navigation	Danger	Infotainment
	App	Assessment	App
Usage Ratio (%)	50	25	25
Task Interarrival Time (sec)	3	5	15
Active/Idle Period (min)	always/0	always/0	always/0
Upload/Download Data (KB)	350/350	500/350	350/500
Task Length (MI)	600	1000	1600
RSU/Edge VM Utilization(%)	6/1.6	20/4	40/8

# Simulation Parameters

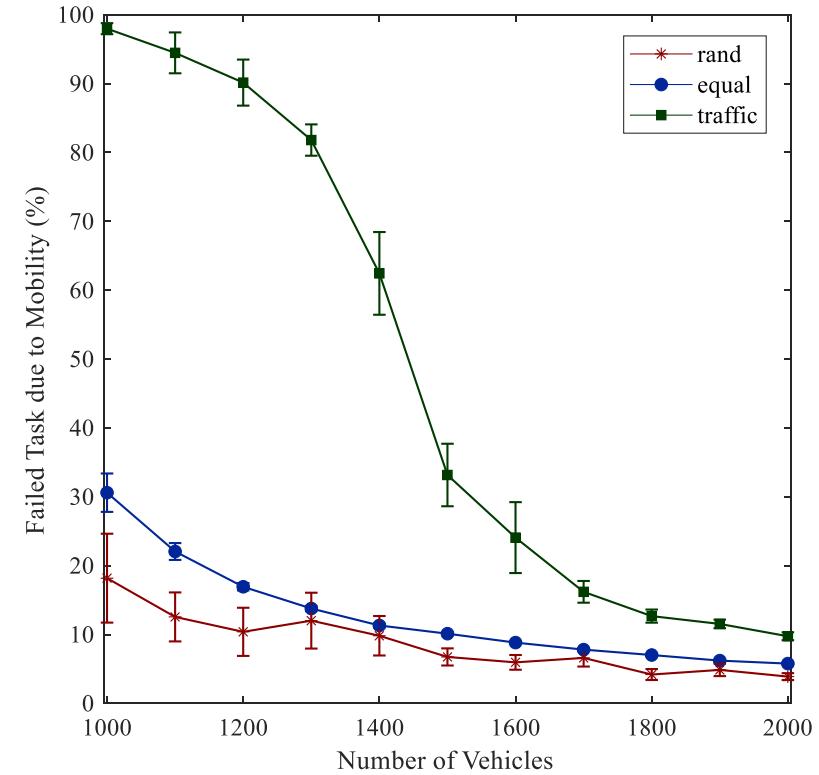
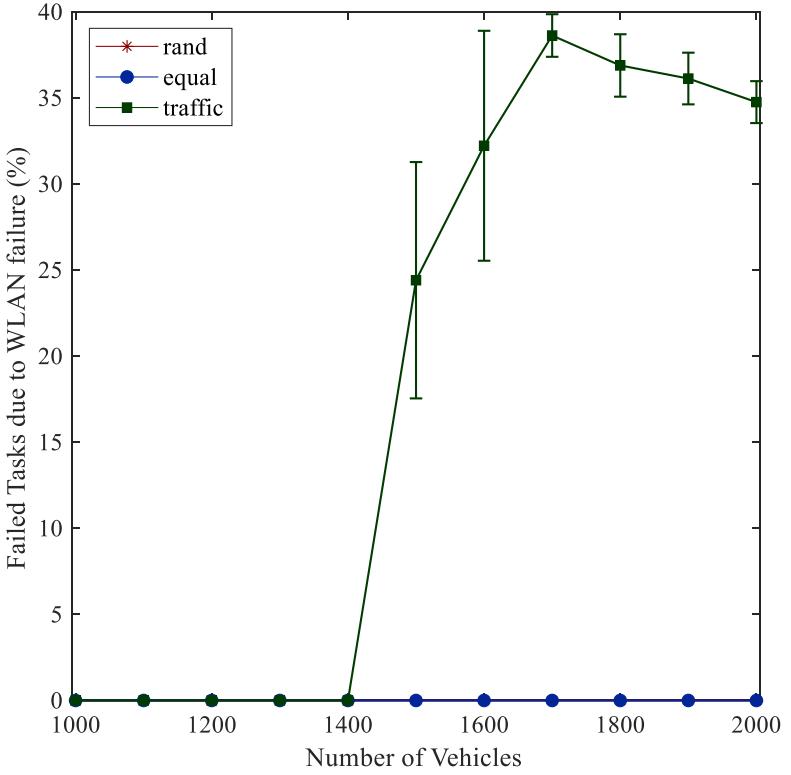
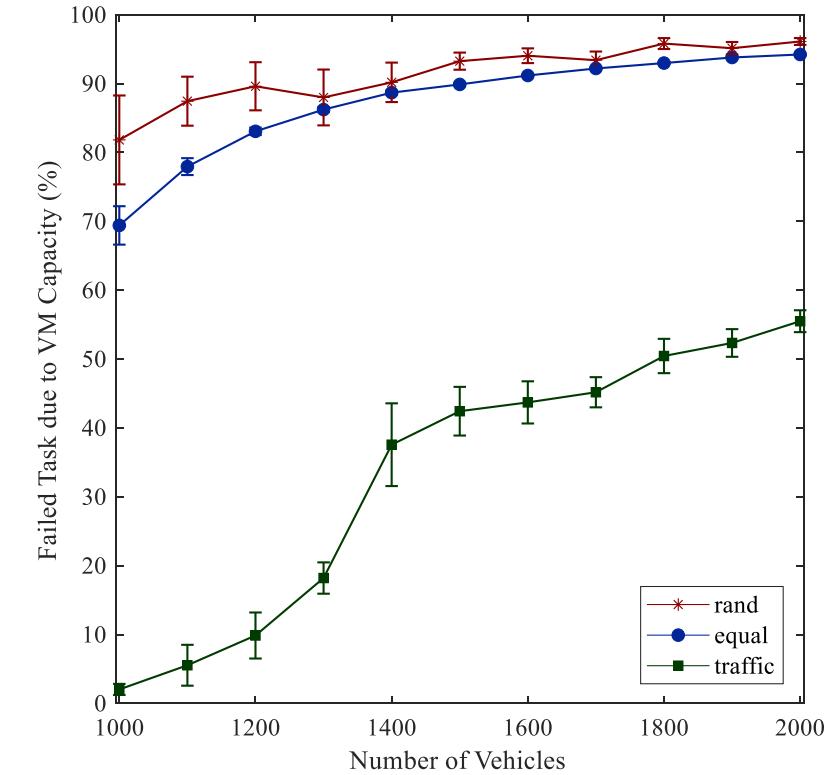
Parameter	Value
Simulation Time/Warm-up Period	15/1 minutes
Number of repetition	10
WLAN Delay Model	Empirical
MAN Delay	Fixed (10 ms)
Number of VM per Edge Host	2
Number of Cores per Edge VM CPU	2
VM Processor Speed per Edge	10-44 GIPS
Mobility Model	Vehicular Mobility
Number of locations for Type 1/2/3 Places	1/4/6
Speed of Vehicles in Type 1/2/3 Places	20/40/60 km/hour

# Important Simulation Results



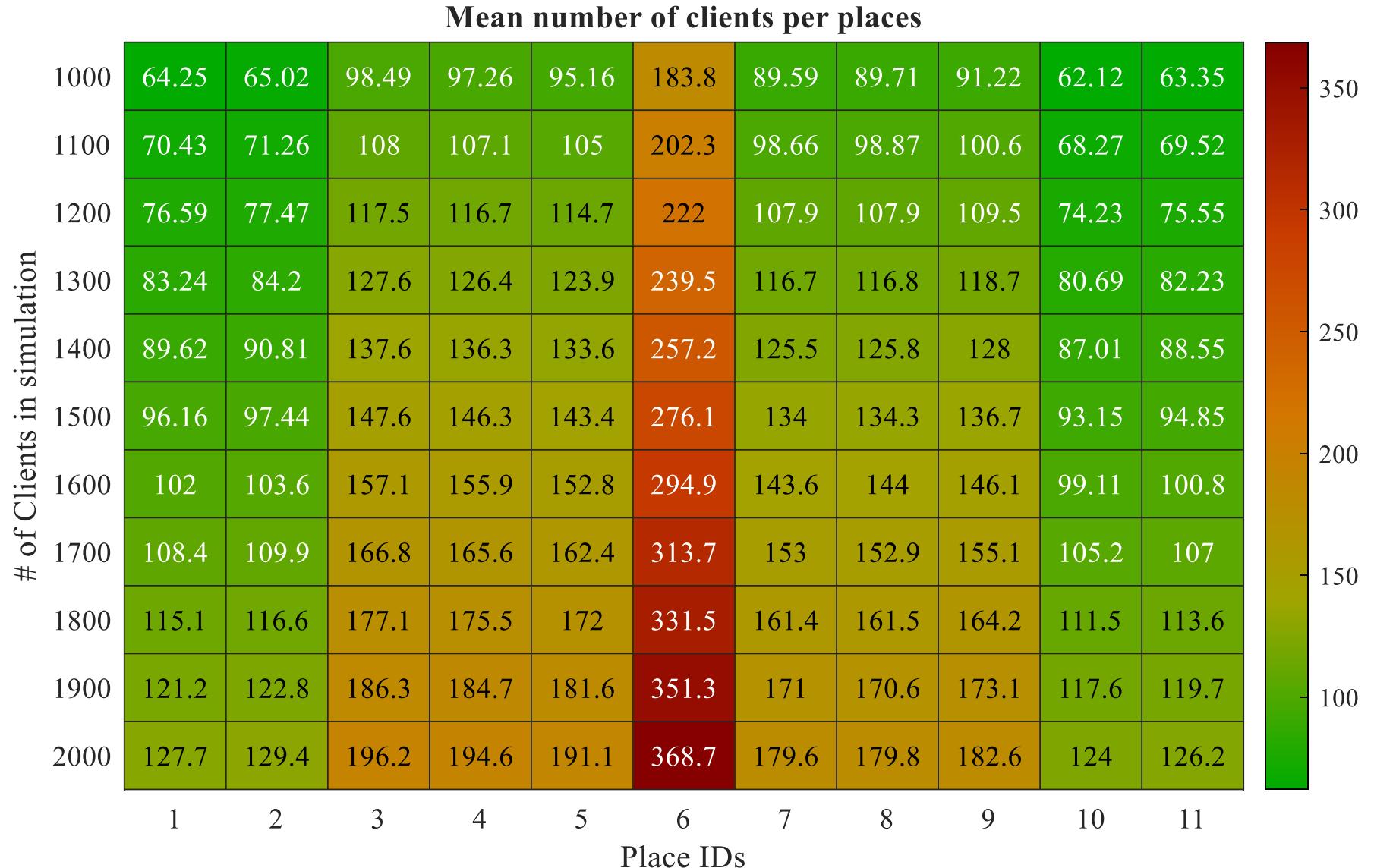
Graph is plotted with 95% confidence interval error bars

# Task Failure Reason Analysis

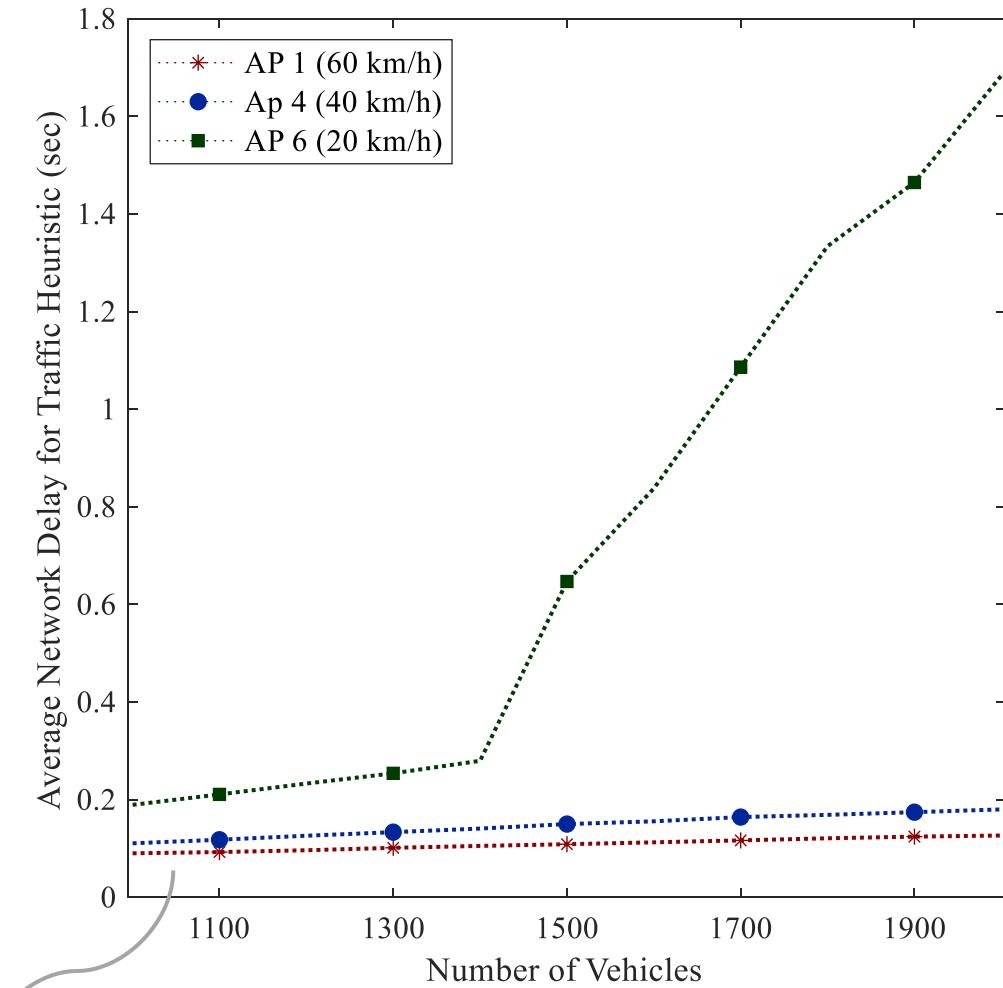
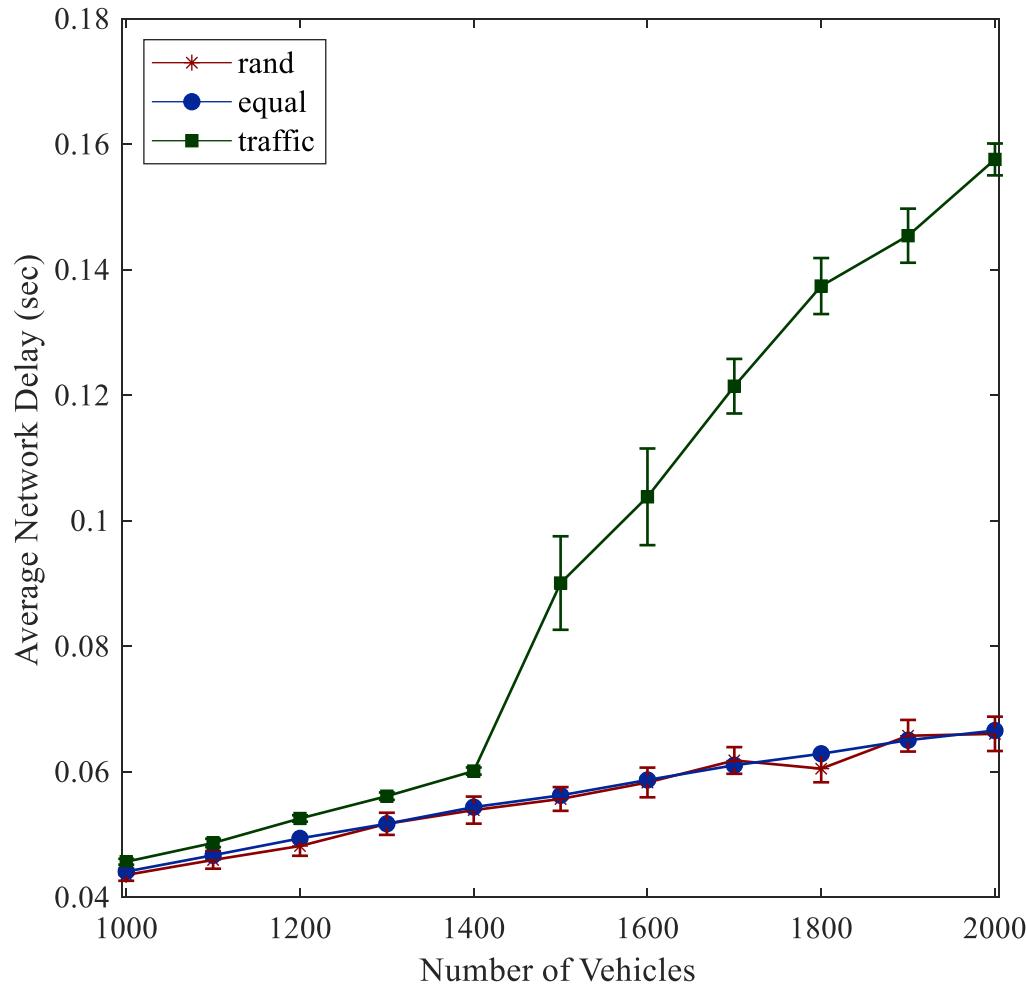


Failed tasks due to mobility dominates the failure reasons

# Mobility Model Verification



# Network Delay Analysis



★ Network delay values of different access points



# Case Study 5 – Network & Server Capacity P.

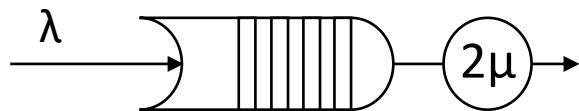
Performance Evaluation of Different Capacity Planning Approaches

Find the source code below:

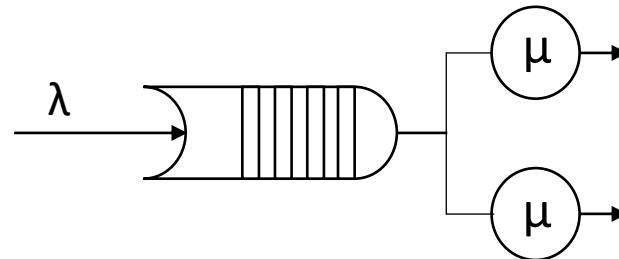
[https://github.com/CagataySonmez/PerformanceEvaluationWithEdgeCloudSim  
/tree/main/src/edu/boun/edgecloudsim/applications/scenario5](https://github.com/CagataySonmez/PerformanceEvaluationWithEdgeCloudSim/tree/main/src/edu/boun/edgecloudsim/applications/scenario5)

# Which One Provides the Best Network Delay?

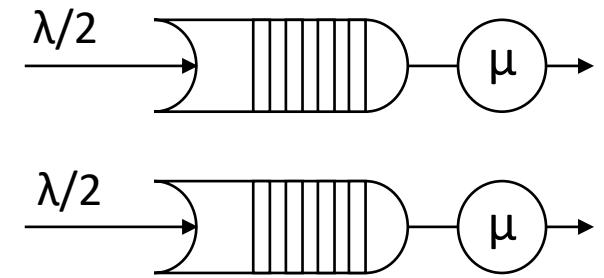
**Case 1**



**Case 2**

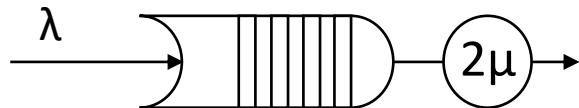


**Case 3**



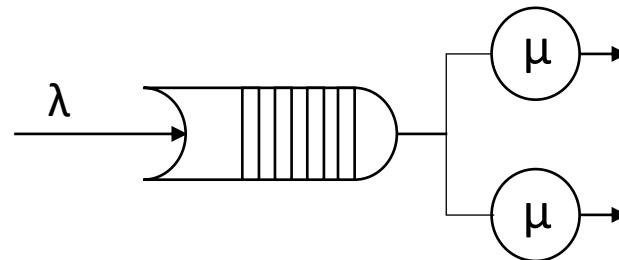
# Which One Provides the Best Network Delay?

**Case 1**



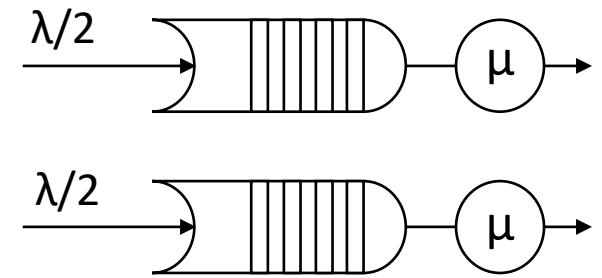
**M/M/1 Queue**

**Case 2**



**M/M/2 Queue**

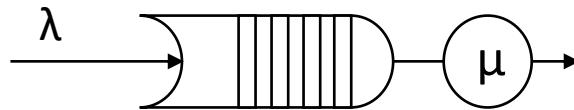
**Case 3**



**Parallel M/M/1 Queues**

# Case 1: M/M/1 Queue

- Arrivals occur at rate  $\lambda$  according to a Poisson process
- Service times have an exponential distribution with rate parameter  $\mu$
- A **single** server serving with first-come first-served discipline



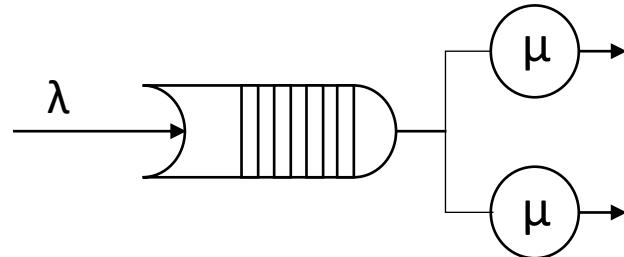
- Response time  $E(T) = \frac{1}{\mu - \lambda}$  ,  $\mu > \lambda$

capacity/packet length (p/s)

rate of the traffic (p/s)

# Case 2: M/M/2 Queue

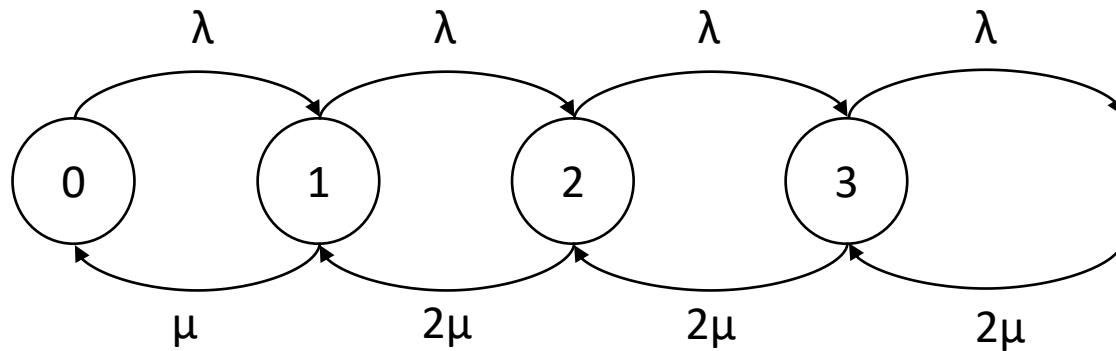
- Arrivals occur at rate  $\lambda$  according to a Poisson process
- Service times have an exponential distribution with rate parameter  $\mu$
- A single queue with **multiple** servers



- Response time can be calculated with birth-death process model

# Case 2: M/M/2 Queue

cont.



$$P_0 \lambda = P_1 \mu$$

$$P_1 (\lambda + \mu) = P_0 \lambda + P_2 2\mu$$

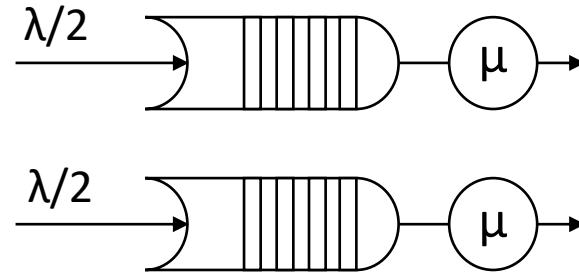
After some math...

$$E(T) = \frac{4\mu}{(2\mu - \lambda)(2\mu + \lambda)}$$

$$P_n (\lambda + 2\mu) = P_{n-1} \lambda + P_{n+1} 2\mu$$

$$\sum P_n = 1$$

# Case 3: Two Parallel M/M/1 Queues

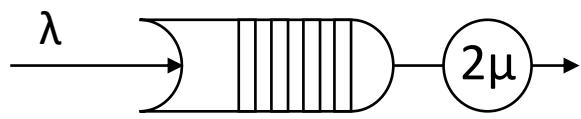


$$E(T) = \frac{1}{\mu - \lambda/2} \times 2$$

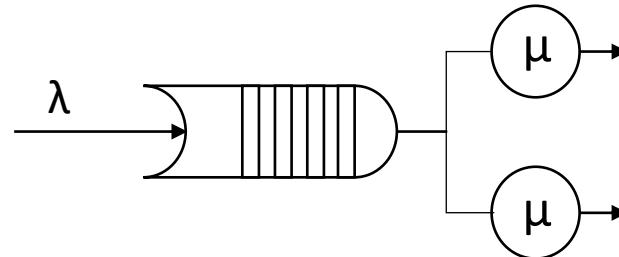
$$E(T) = \frac{4}{2\mu - \lambda}$$

# Expected Network Delay for All Cases

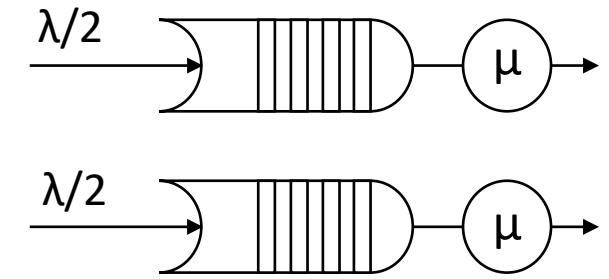
**Case 1**



**Case 2**

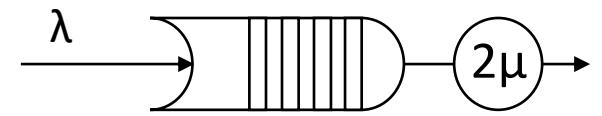
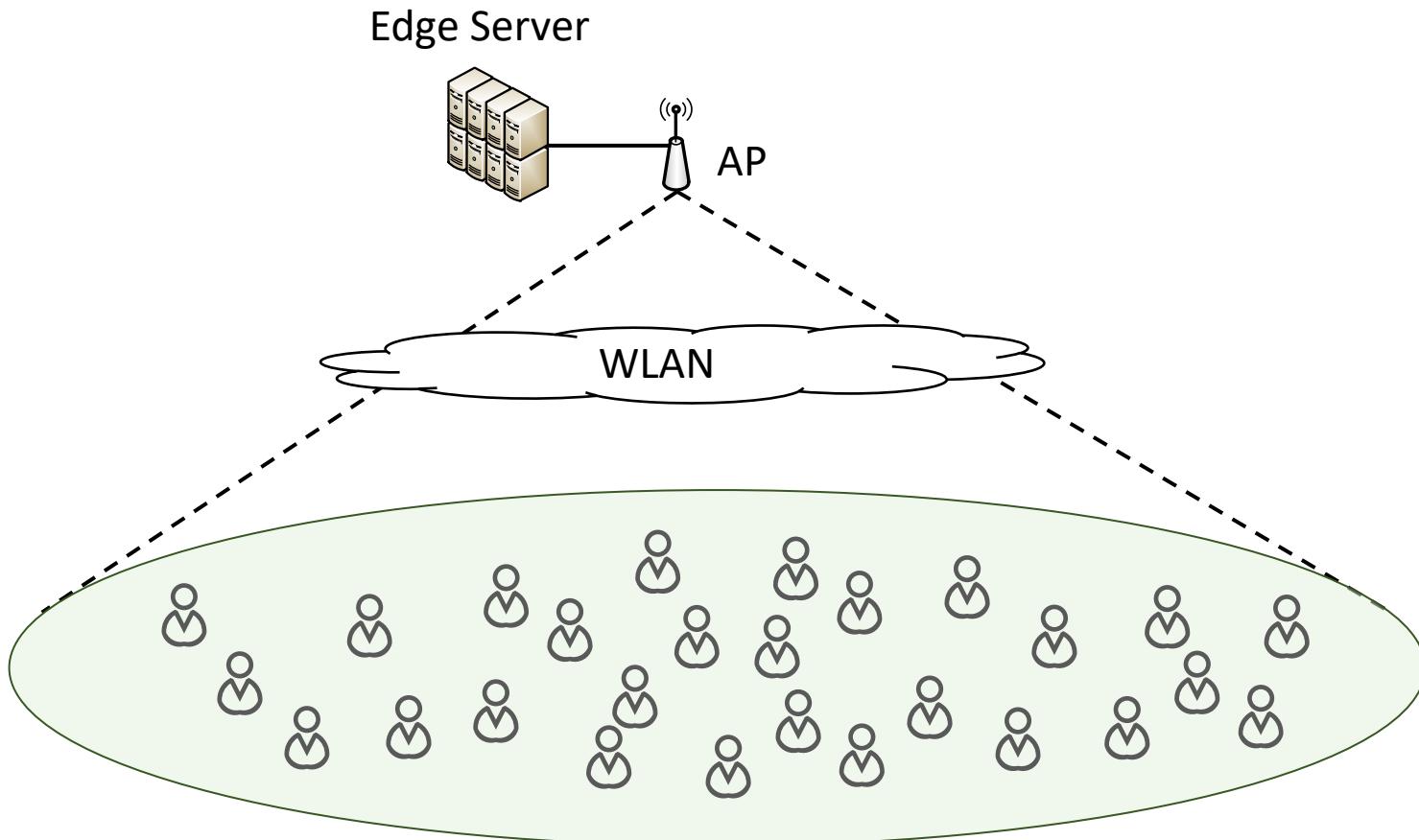


**Case 3**



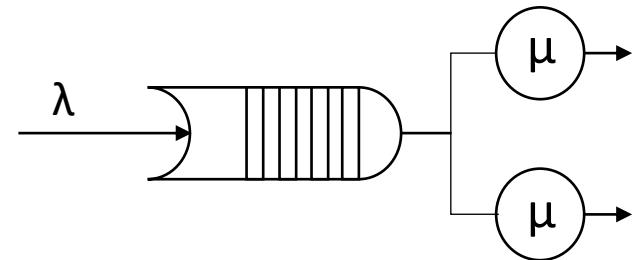
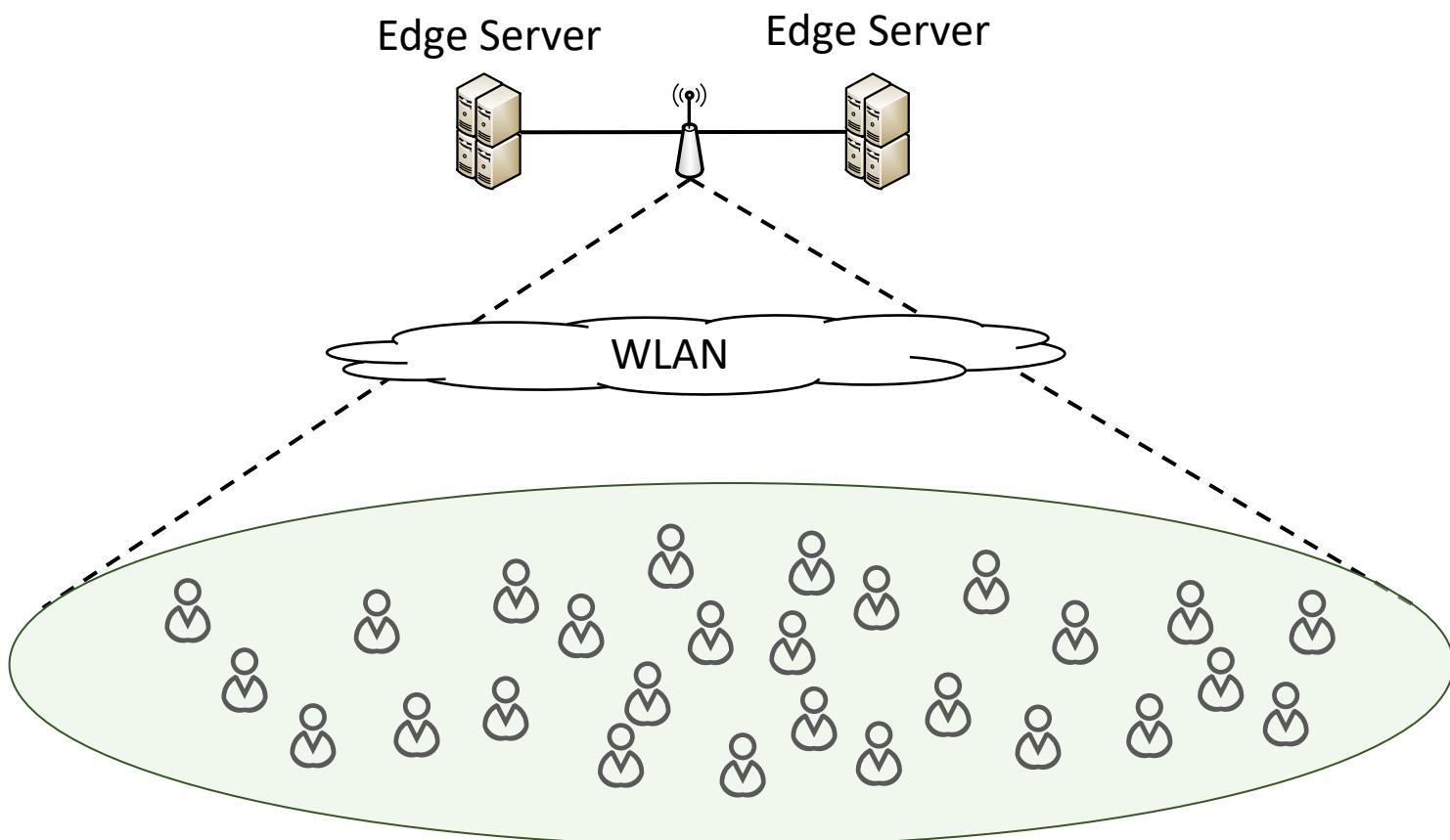
$$E(T) = \frac{1}{2\mu - \lambda} < E(T) = \frac{4\mu}{(2\mu - \lambda)(2\mu + \lambda)} < E(T) = \frac{4}{2\mu - \lambda}$$

# Implementation of Case1



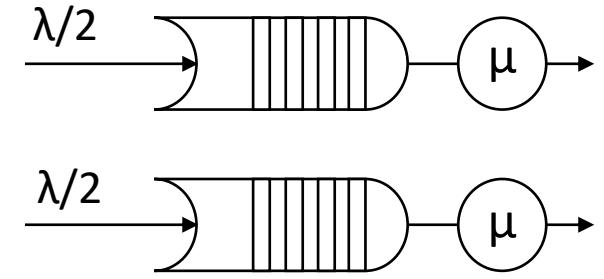
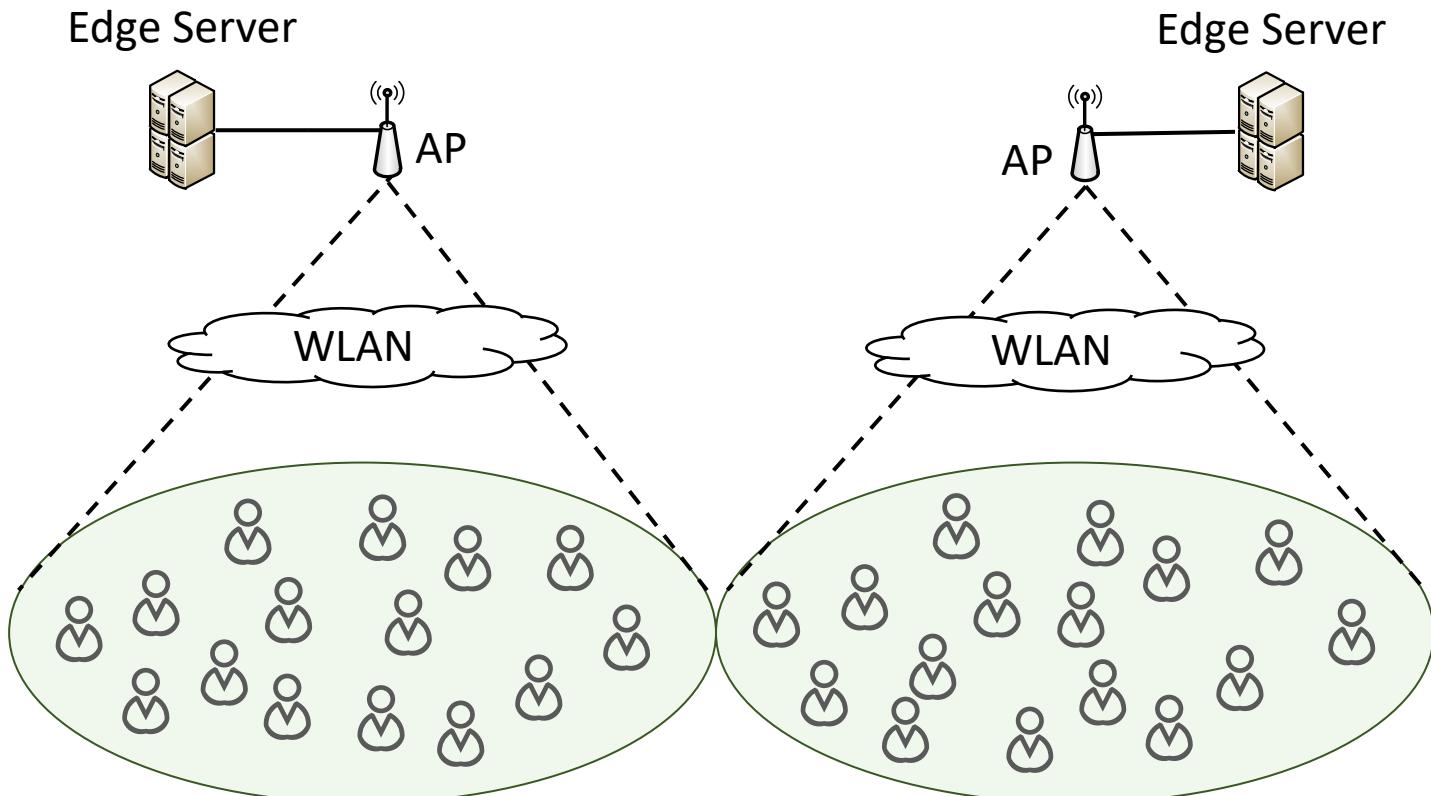
Parameter	Value
WLAN Bandwidth	100 Mbps
# of Core for Edge Server	4
Capacity of Edge Server	20 GIPS

# Implementation of Case2



Parameter	Value
WLAN Bandwidth	50 Mbps
# of Cores per Edge Servers	2
Capacity of Edge Servers	10 GIPS

# Implementation of Case3



Parameter	Value
WLAN Bandwidth	50 Mbps
# of Core per Edge Servers	2
Capacity of Edge Servers	10 GIPS

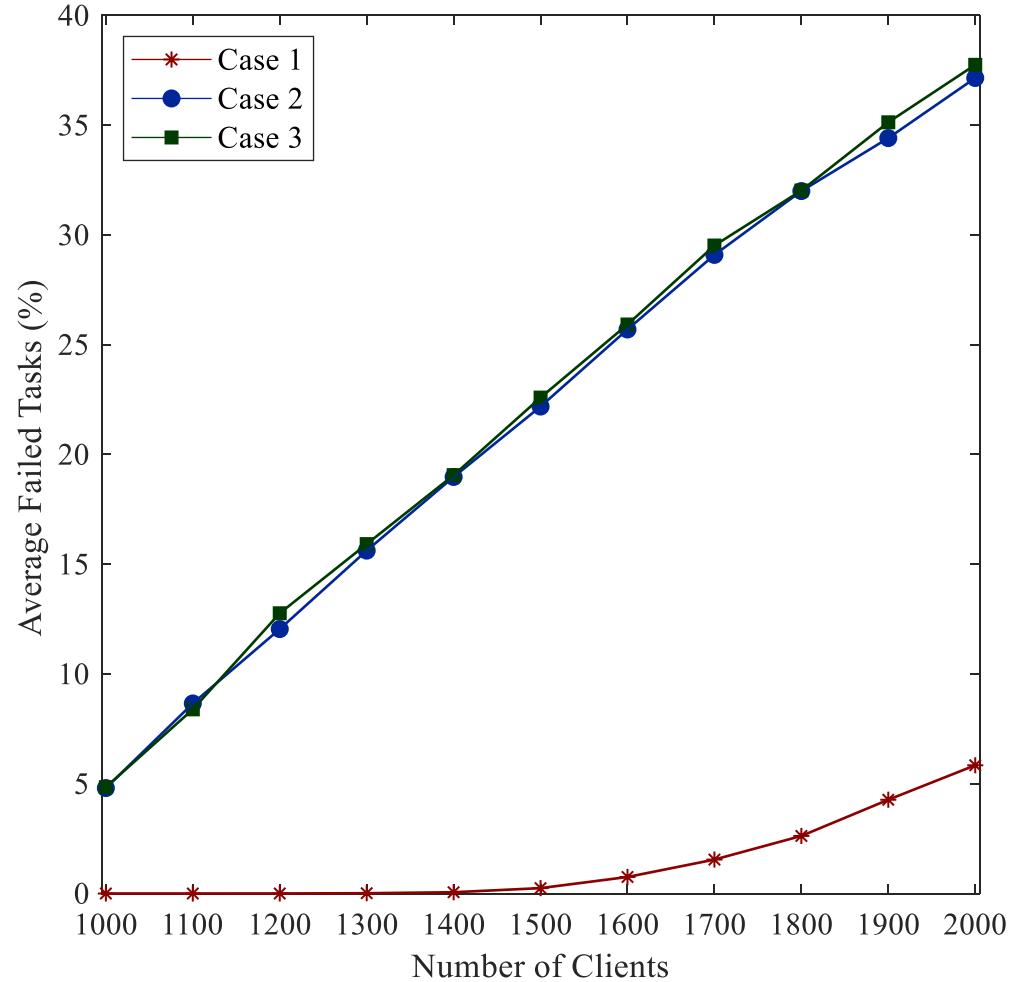
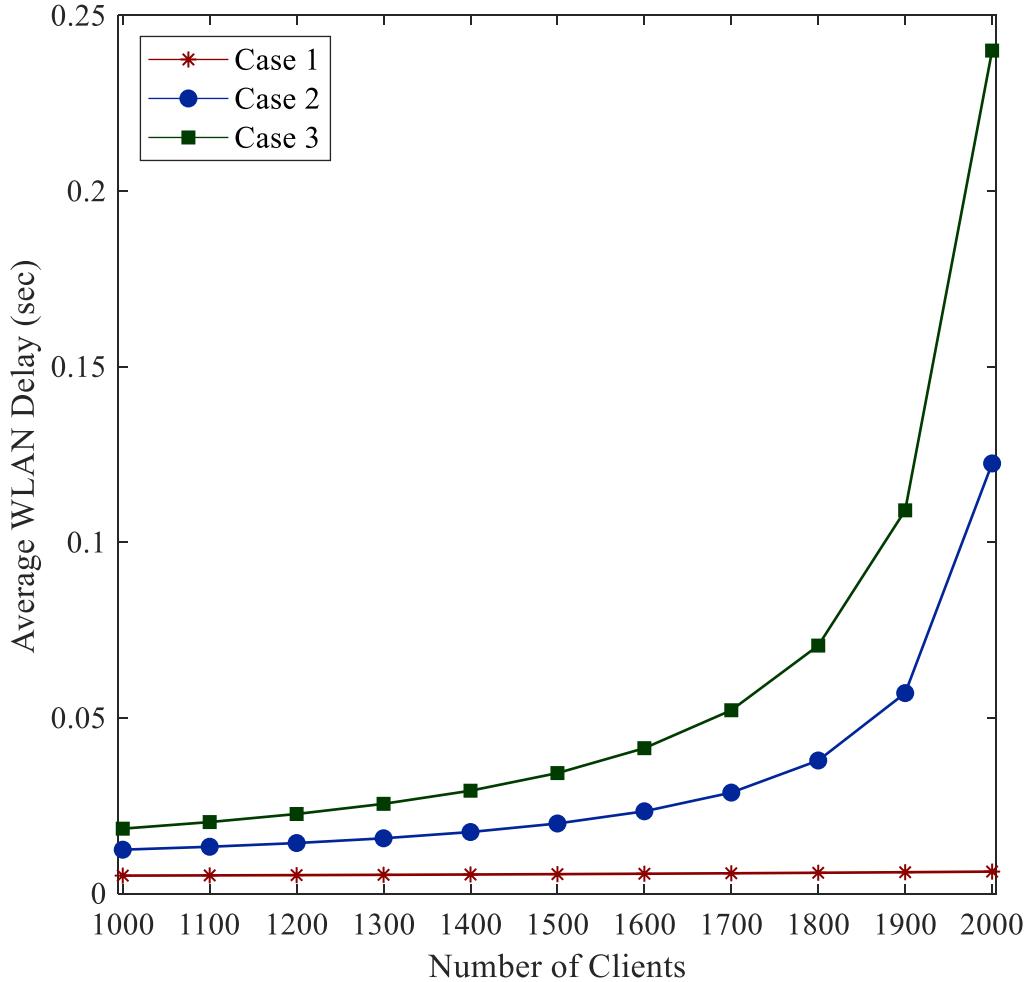
# Application Used in Simulations

Parameter	Sample App
Task Interarrival (sec)	5
Active/Idle Period (sec)	30/1
VM Utilization on Edge/Cloud (%)	3
Task Length (GI)	500
Upload Data Size (KB)	30
Download Data Size (KB)	30

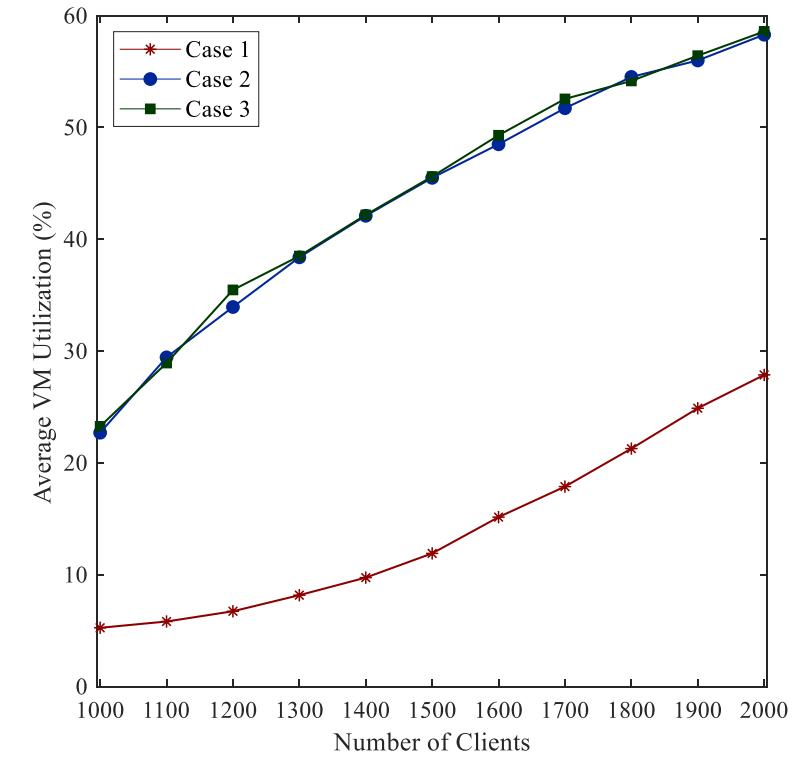
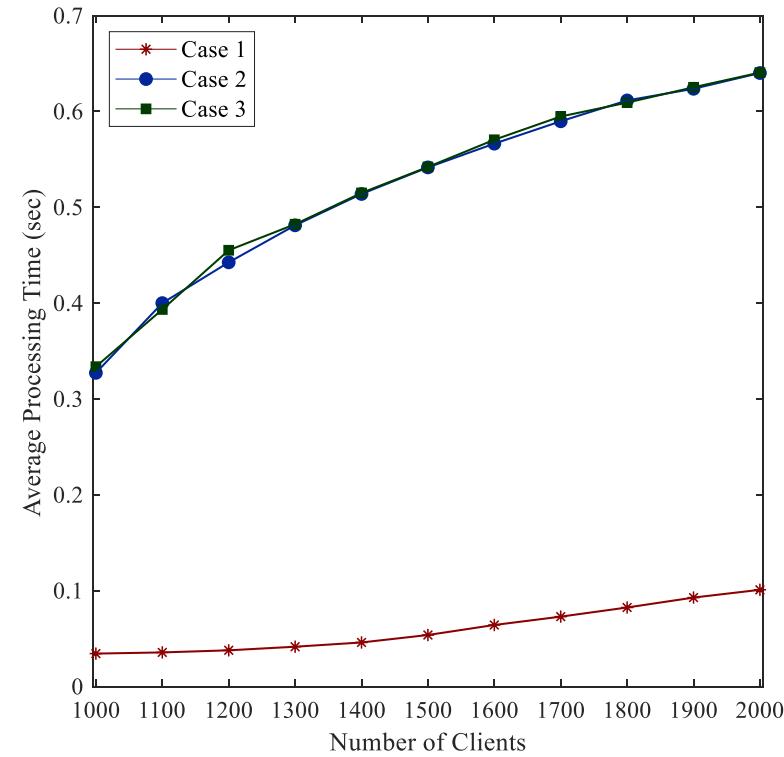
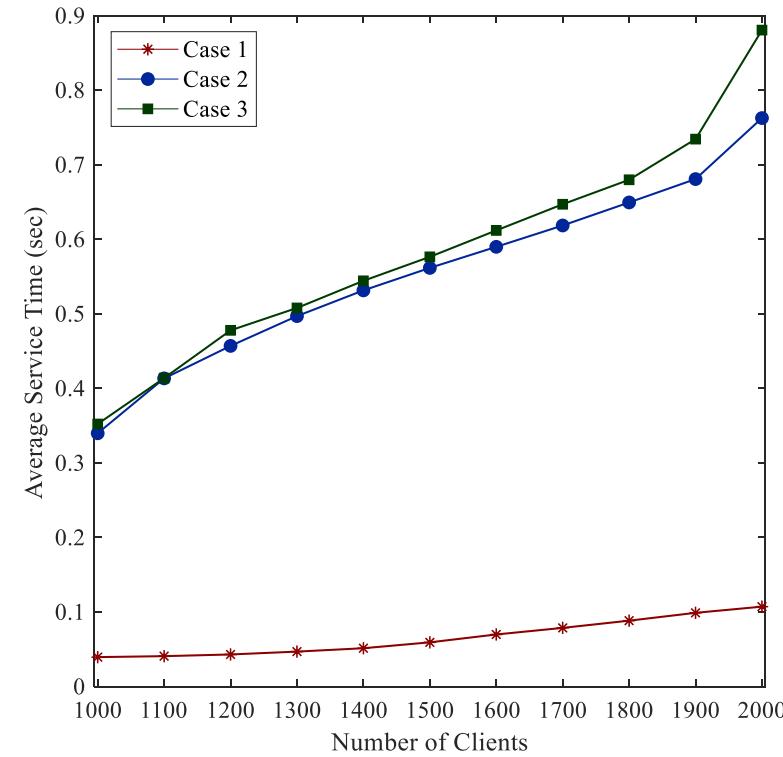
# Simulation Parameters

Parameter	Value
Simulation Time	30 minutes
Warm-up Period	5 minutes
Number of repetition	25
Mobility Model	Nomadic Mobility
Number of Mobile Clients	1000 to 2000
Length of the Simulated Area	6 KM

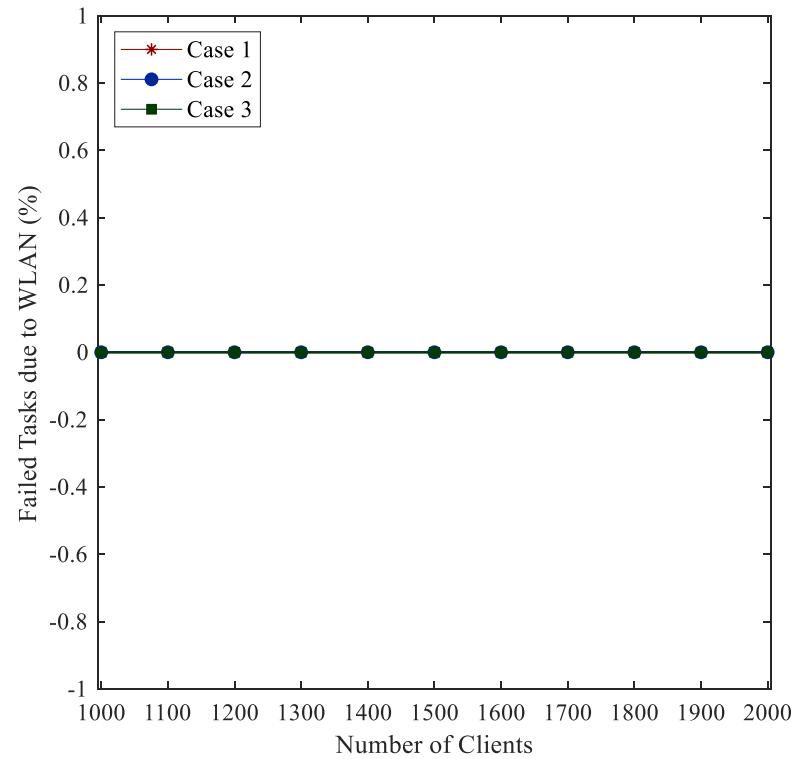
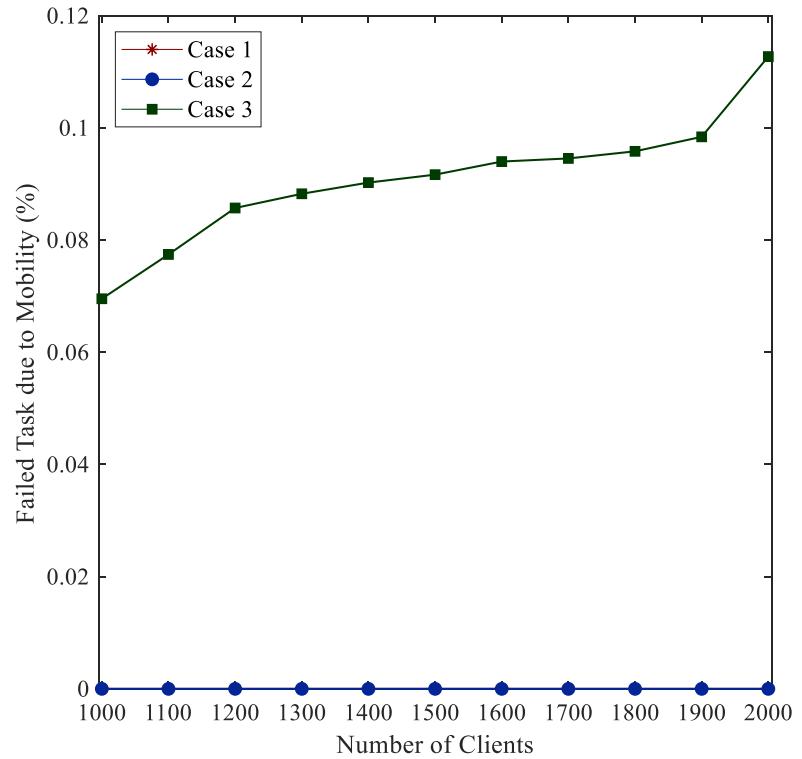
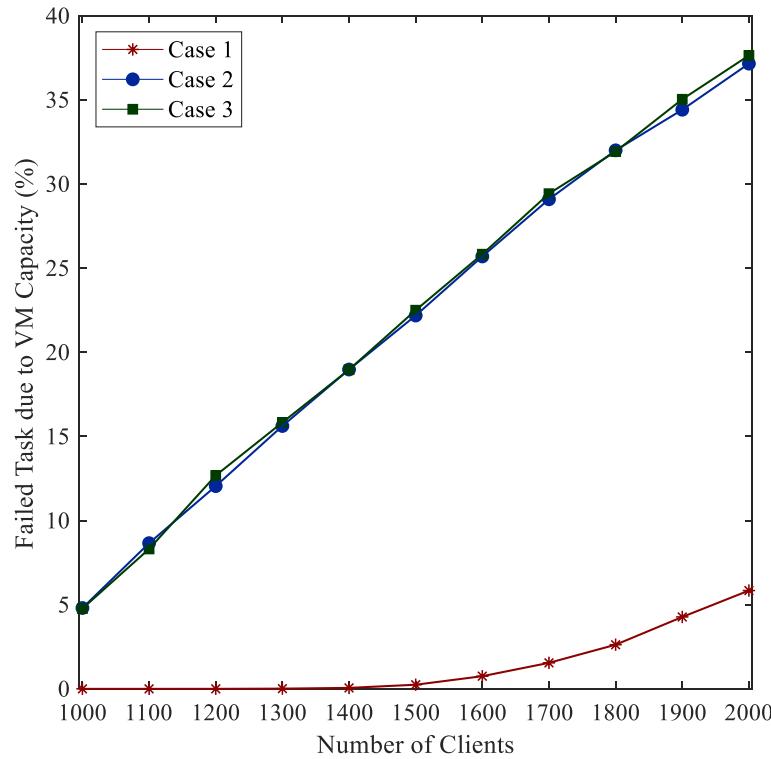
# Average WLAN Delay & Success Rate



# Edge Server Side Statistics



# Task Failure Reasons



# Thank You



# References

- [1] Calheiros, R. N., R. Ranjan, A. Beloglazov, C. A. F. De Rose and R. Buyya, "CloudSim: A Toolkit for Modeling and Simulation of Cloud Computing Environments and Evaluation of Resource Provisioning Algorithms", *Softw. Pract. Exper.*, Vol. 41, No. 1, pp. 23–50, Jan. 2011.
- [2] Howell, Fred, and Ross McNab. "SimJava: A discrete event simulation library for java." *Simulation Series* 30 (1998): 51-56.
- [3] Gupta, Harshit, Amir Vahid Dastjerdi, Soumya K. Ghosh, and Rajkumar Buyya. "iFogSim: A toolkit for modeling and simulation of resource management techniques in the Internet of Things, Edge and Fog computing environments." *Software: Practice and Experience* 47, no. 9 (2017): 1275-1296.
- [4] Brogi, Antonio, and Stefano Forti. "QoS-aware deployment of IoT applications through the fog." *IEEE Internet of Things Journal* 4, no. 5 (2017): 1185-1192.
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- [6] Tuli, Shreshth, Redowan Mahmud, Shikhar Tuli, and Rajkumar Buyya. "Fogbus: A blockchain-based lightweight framework for edge and fog computing." *Journal of Systems and Software* 154 (2019): 22-36.
- [7] Qayyum, Tariq, Asad Waqar Malik, Muazzam A. Khan Khattak, Osman Khalid, and Samee U. Khan. "FogNetSim++: A toolkit for modeling and simulation of distributed fog environment." *IEEE Access* 6 (2018): 63570-63583.
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- [10] R. Mayer, L. Graser, H. Gupta, E. Saurez and U. Ramachandran, "EmuFog: Extensible and scalable emulation of large-scale fog computing infrastructures," 2017 *IEEE Fog World Congress (FWC)*, 2017, pp. 1-6.
- [11] M. Etemad, M. Aazam and M. St-Hilaire, "Using DEVS for modeling and simulating a Fog Computing environment," 2017 *International Conference on Computing, Networking and Communications (ICNC)*, 2017, pp. 849-854.
- [12] "EdgeCloudSim Discussion Forum", <https://groups.google.com/u/1/g/edgecloudsim>, accessed in October 2022.
- [13] "EdgeCloudSim YouTube Channel", <https://www.youtube.com/channel/UC2gnXTWHHN6h4bk1D5gpcIA>, accessed in October 2022.