

Emulation Framework for AIoT Federated Learning

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1 Abstract

Federated Learning (FL) allows a fleet of devices to collaborate towards a globally trained machine learning model. However, applications of FL for low-powered Artificial Intelligence Internet of Things (AIoT) devices continue to face key challenges in limited computing resources and network limitations. Although researchers have continued to produce novel algorithms to tackle these issues, measuring this performance through a realistic benchmark would require one to procure a large fleet of devices which is often infeasible and costly. The key role of software simulation is thus to provide the tools to assist in the process. Software systems can allow reserchers to tweak FL system parameters such as the number of clients, as well as view metrics such as network costs and training time. This allows them to validate new ideas easily. However, simulation that is hardware-agnostic is not enough, especially for embedded devices where machine learning support is not standardized. Hence, this work introduces a software emulation framework called “zfl”, utilizing QEMU and the Zephyr OS to streamline the process of building a fleet of clients and allow validation testing of an entire FL system lifecycle that is hardware dependent.

2 Acknowledgements

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3 Introduction

Federated Learning (FL) emerged as a method for solving key issues with the standard centralized learning approach, namely, it achieves the following properties:

- **Data Privacy:** a centralized training approach involves the need for the centralized machine performing the computation to have full access to the entire data set. With FL, data never leaves each individual client’s device. Instead, only the updated weights are shared to form the global model.
- **Scalability:** FL enables leveraging a network to perform computation in parallel.

These properties makes FL widely used in in the context of Artificial Intelligence of Things (AIoT) devices. By leveraging the vast amount of data generated by IoT devices, FL harnesses the collective intelligence of edge devices while respecting data sovereignty and privacy regulations. For example, Android utilized FL training on user interactions for Smart Text Selection, which predicts the desired set of words around a user’s tap[1].

While FL has been successful in these aspects, there are a few limitations to the approach which may not make FL as effective in some applications. In particular, areas which require low-powered devices face key challenges such as:

- **Limited computing resources:** individual devices may face memory constraints, limiting the size of the local model it is able to train. Constraints on computing power also lead to longer training times. This is particularly so for low-powered IoT devices.
- **Network limitations:** communication speed can become the bottleneck for performance as IoT devices rely on unstable wireless communication networks. Furthermore, data constraints can exist such that the number of bytes sent may be a cost inducing factor.

Hence, the development of FL algorithms often seek to advance progress towards solving the aforementioned issues.

3.1 Problem

Prior to effectively deploying FL, different factors including the convergence rate and model accuracy needs to be well studied. This gives rise to the need for soft-

ware simulation. However, the simulation of FL in the distributed setting involves dealing with issues which do not arise in datacenter ML research. These include running on different simulated devices, each with potentially varying amounts of data. Furthermore, metrics such as the number of bytes transferred by the device, as well as the ability to simulate real-world issues such as client drop-out, can also be important for proposed FL algorithms to handle.

3.2 Literary Review

FLSim[2] aims to provide a simulation framework for FL by offering its users a set of software components – which can then be mixed and matched to create a simulator for their use case. Developers need only define the data, model and metrics reported, and FL system parameters can be altered in a JSON configuration file. FLUTE[3] adds additional features by allowing users to gain access to cloud based compute and data. However, these simulation solutions are consequently hardware-agnostic. Without taking into account the specific platforms which FL is performed on, these simulators cannot provide insight into whether the system will work in the production environment.

In contrast, FedML[4] is a research-oriented library which supports various algorithms and 3 platforms, on-device training for IoT and mobile devices, distributed computing and single-machine simulation. Simulation is offered through the FedML Parrot[5], which offers an accelerated simulation framework employing multiple optimizations to improve simulation speed. However, on-device training is supported only on Raspberry Pi 4 and NVIDIA Jetson Nano which limits hardware validation to these 2 devices.

One approach to acquiring hardware dependent results is to emulate the hardware environment. This can be achieved through software systems. One such system explored the combination of Quick Emulator (QEMU) and Zephyr, a real time operating system to emulate embedded devices in the machine learning context[6]. However, this approach only emulated machine learning inference rather than on-device training.

Here, this work proposes a new emulation framework “zfl”, which aims to achieve the following properties:

- Provide better insight into hardware specific support by running FL on emulated hardware through QEMU and Zephyr OS.

- Collect useful metrics during the FL lifecycle, especially on variables typically difficult to simulate.
- Support simulation of real world scenarios such as variable data and network packet loss.

3.3 QEMU

QEMU[7] is an open source machine emulator and virtualizer. It enables system emulation, creating a virtual model of an entire machine (CPU, memory and emulated devices) to run a guest OS. In this mode, the CPU may be fully emulated, or it may work with a hypervisor to allow the guest to run directly on the host CPU. In zfl, QEMU with full CPU emulation is used without a hypervisor as part of its software architecture to emulate hardware. Note that by default, the framework is built for QEMU x86 32-bit, which entails the use of the qemu-i386 binary in section 4.

3.4 Zephyr OS

To emulate the issue of limited computing resources, it is important to make use of system runtimes used by those devices. Zephyr OS[8] is one such operating system. It is based on a small-footprint kernel designed for use on resource-constrained and embedded systems: from simple embedded environmental sensors and LED wearables to sophisticated embedded controllers, smart watches, and IoT wireless applications. Furthermore, Zephyr is highly configurable, allowing the user to choose only the specific kernel services required, and also delve into lower level memory mapping of the system SRAM and DRAM. Most importantly, Zephyr supports a wide range of CPU architectures including ARM, RISC-V and x86. Zephyr also provides built-in capabilities for building for the QEMU environment, and implements key features such as networking through the QEMU built-in Ethernet adapter. In zfl, client code will be written to work in the Zephyr OS environment.

4 Implementation

The framework implements the classical FedAvg algorithm[9] as part of its simulation, where each client sends its updated model weights to a central server, which then performs aggregation using simple averaging. Hence, the architecture of the

framework is based on the assumption of multiple clients talking to a single server.

To run on Zephyr OS, the entire software stack is developed in the C programming language. Although Zephyr also supports applications written in C++, the C programming language would make the framework more suitable to run on embedded devices. Note that the framework is implemented for Linux and all tests are run on a Debian based machine¹.

4.1 Configuration

In order to run machine learning training on each client, some configuration is required to ensure that we have sufficient memory to allocate for the neural network model and training data. Depending on the architecture of the model and the size of the data, these options may need to be further tweaked to prevent any runtime memory allocation crashes. Listing 1 shows the options made to `prj.conf` to create a runtime capable of up to 10MB of heap memory. Listing 2 shows the configuration made to the QEMU board under `qemu_x86.dts` for a total DRAM size of 15MB. This is in excess of the heap memory size as additional memory is reserved for the kernel image and stack memory.

```
1 CONFIG_SRAM_SIZE=15360
2 CONFIG_MAIN_STACK_SIZE=8192
3 CONFIG_KERNEL_VM_SIZE=0
  x7000000
4 CONFIG_HEAP_MEM_POOL_SIZE
  =10485760
```

Listing 1: Zephyr prj.conf

```
1 #define DT_DRAM_SIZE
  DT_SIZE_K(15360)
```

Listing 2: QEMU board.dts

The main `zfl` binary is used to bootstrap either the client or server aspects of FL simulation. Listing 3 shows the different options available for configuring FL parameters and their meanings.

```
1 ./zfl client -c num_clients -e epochs -b batch_size
2 # -c num_clients: Number of clients to boot up.
3 # -e epochs:      Number of epochs (training passes on the entire
  data set).
4 # -b batch_size:  Number of training labels used for a single
  update.
5
6 ./zfl server -r num_rounds -c clients_per_round
```

¹Source code available under a GPL license at <https://github.com/bbawj/zfl>

```

7 # -r num_rounds:      Number of rounds of aggregation.
8 # -c clients_per_round: Number of clients that need to respond to
   start a round.

```

Listing 3: The main zfl binary

4.2 Bootstrapping Process

Next the framework needed a method for spawning an arbitrary number of QEMU instances, and allowing these instances to communicate back to the server. When called in client mode (Listing 5), zfl accomplishes this by making use of the “fork” and “exec” pattern with the desired number of clients.

However, each instance of QEMU persists in an isolated network different from the host PC, and is not able to communicate. We can bypass this limitation using a network bridge to act as a virtual network device forwarding packets between connected network devices. The network bridge is set up on the host under the name “zfl” with a set of network parameters using the `ip` command line utility as shown in Listing 4.

```

1 ip link add $INTERFACE type bridge
2 ip addr add $IPV4_ADDR_1 dev $INTERFACE
3 ip link set enp61s0 master $INTERFACE
4 ip route add $IPV4_ROUTE_1 dev $INTERFACE > /dev/null 2>&1
5 ip link set dev $INTERFACE up

```

Listing 4: Network bridge setup

To tell QEMU to use it, we pass the name of the bridge along with a randomly generated MAC address as arguments to the `-nic` flag:

```
-nic bridge,model=e1000,mac=%s,br=zfl
```

Although each QEMU client is now able to communicate with the host via the NIC adapter, we still needed a way to monitor the output of each instance. One method is to transmit output and logs over the network. However, this would not allow important crash logs and stacktrace information to be transmitted as the application software would have shutdown. To overcome this, the host creates a named or FIFO pipe for each client, which then is passed into QEMU through the `-serial` flag. Now, all standard output goes through the named pipe, ready to be read by the host. Another outcome of this is that the host is also able to send input to each instance, whose importance will be described in the next

section. Listing 5 showcases how each feature is configured through the QEMU command line binary.

```
1 pid_t child = fork();
2 if (child < 0) {
3     printf("ERROR: could not fork client %d: %s\n", i, strerror(
4         errno));
5     return 1;
6 }
7 ...
8 // generate serial arguments
9 char serial_arg[80];
10 snprintf(serial_arg, 80, "pipe:%s", pipe_path);
11
12 // generate nic arguments
13 char nic_arg[100];
14 char *mac = generate_random_mac();
15 snprintf(nic_arg, sizeof(nic_arg), "bridge,model=e1000,mac=%s,br=
16     zfl", mac);
17
18 // start client as new process
19 execlp("qemu-system-i386", "qemu-system-i386",
20     "-m", "15", "-cpu", "qemu32,+nx,+pae", "-machine", "q35",
21     "-device", "isa-debug-exit,iobase=0xf4,iosize=0x04",
22
23     "-no-reboot", "-nographic", "-no-acpi",
24
25     "-serial", serial_arg,
26
27     "-nic", nic_arg,
28
29     "-kernel", "./zflclient/out/zephyr/zephyr.elf",
30
31     NULL);
```

Listing 5: Client forking process

In addition to the NIC adapter configuration, each client needed a unique Internet Protocol Version 4 (IPv4) address in order to establish TCP based connections with the central server. Samples provided by Zephyr OS describe a way to achieve this by setting a compile time configuration flag `CONFIG_NET_CONFIG_MY_IPV4_ADDR`. However, this is impractical to scale to a large number of clients, since each client would need a separately compiled bi-

nary. One solution to this problem is to assign the IPv4 address dynamically using the built-in Zephyr network function[10]:

`net_if_ipv4_addr_add`

To achieve this, each client starts off as a Zephyr shell instance and a user-defined command `run` is registered. This exposes a shell command that takes in a command line argument which defines the desired IP address of the instance (Listing 6). Finally, this command triggers the `run` function (Listing 7) as a way to start the main program.

Overall, the complete emulation architecture is illustrated in figure 1, describing the interactions between the host system and guest instances.

```
1 SHELL_CMD_ARG_REGISTER(run, NULL, "Run with IPv4 address", run,
   4, 0);
```

Listing 6: Registering user defined command “run” to the function pointer `run`

```
1 int run(const struct shell *sh, size_t argc, char **argv) {
2     // ...
3     char *addr_str = argv[1];
4     LOG_INF("instance ipaddr is %s", addr_str);
5     struct in_addr addr;
6     zsock_inet_pton(AF_INET, addr_str, &addr);
7     if (!net_if_ipv4_addr_add(net_if_get_default(), &addr,
8     NET_ADDR_MANUAL, UINT32_MAX)) {
9         LOG_ERR("failed to add %s to interface", addr_str);
10        return -1;
11    }
12    // ...
13 }
```

Listing 7: The “run” function which performs IP address assignment at runtime

4.3 Client

The first step within the internal implementation of each client is to establish TCP socket connection to the central server and obtain their assigned ID. This is then used to obtain the training data from the server which corresponds to that ID. Thus, this process allows for training data to be dynamically assigned to different instances. Finally, each client starts a HTTP server and marks itself as ready

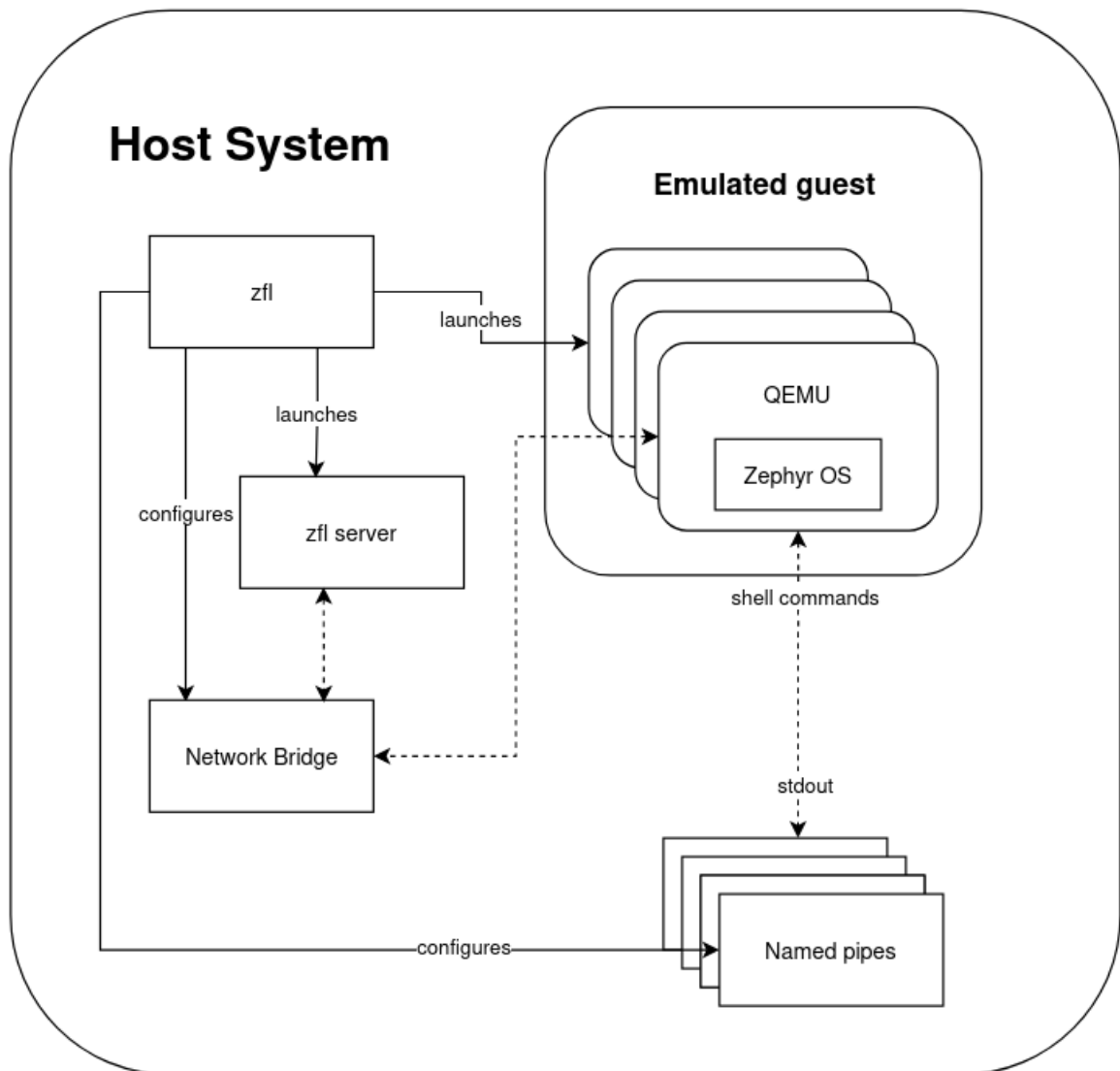


Figure 1: Host-guest emulation architecture

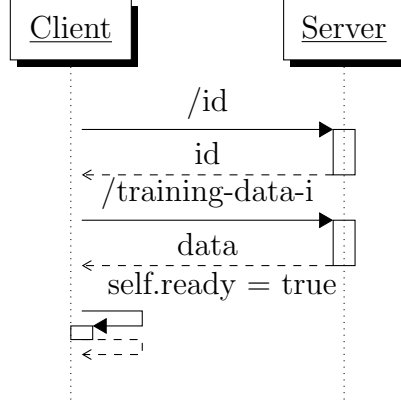


Figure 2: Client initialization sequence

to begin the training round. The complete initialization process is illustrated in Figure 2.

4.3.1 Machine Learning

Once initialized, clients wait for a request to their `start` HTTP endpoint. This triggers the `train` function, which performs forwarding and backpropagation on the local data set. The underlying neural network implementation utilizes `nn.h`[11], an open source educational neural network C library. Porting the library for use included updating traditional POSIX syscalls to the Zephyr kernel syscalls. However, further modifications were made for specific use as described in section 5.

4.3.2 Metrics

The benefit of using emulated hardware is the ability to collect real statistics during the operation of the machine. The Zephyr OS exposes kernel APIs for user applications to query for network statistics such as bytes sent and received, as well as specific network L3 and L4 data including the number of IP and TCP packets dropped and retransmitted.

```
net_mgmt(NET_REQUEST_STATS_GET_TCP, NULL, &data, sizeof(data));
```

This data is queried by each client and sent together with their updated weights. The total training time in seconds is also tallied. This is displayed along with additional details such as the current round, number of ready clients, as well as a graph of the validation set loss and accuracy on a simple graphical user interface shown in Figure 5.

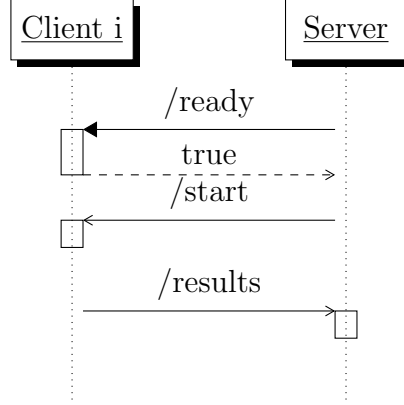


Figure 3: FL round

4.4 Server

The central server runs on the host machine without needing additional configuration. Its primary purpose is to aggregate individual client weights every round. Implemented HTTP endpoints are described in figure 4. After assigning each connecting client their ID and training data, it performs the function `start_round` at an interval of 10 seconds. Each time, the server pings all previously connected clients to check if they are ready to start the training round. When enough clients are ready, it sends a HTTP POST request to the `start` endpoint of the client, which then triggers the training function. Once the client has completed its training, it sends the resulting weights of the local model to the HTTP POST endpoint `results` of the server, which then performs the aggregation. The sequence of events for a single round is illustrated in Figure 3.

4.4.1 Scenario Emulation

zfl takes advantage of the emulated architecture to introduce hooks into tools which can emulate interesting scenarios. Passing the “-loss” flag into `zflserver` will enable packet loss emulation using the Linux Traffic Control[12] tool on the network interface between the server and clients. The flag translates to this command which adds 10% packet loss to our `zfl` network interface:

```
sudo tc qdisc add dev zfl root netem loss 10%
```

Other options can also be ported in this similar fashion to provide a wide variety of network emulation capabilities during the federated learning lifecycle.

Client		
Endpoint	HTTP Method	Description
/start	POST	Initiates training round using updated weights with JSON body: {weights: int}
/ready	GET	Gets client ready status
Server		
/results?id=	POST	Client id submits results with JSON body: {round: int, weights: string}
/id	GET	Obtain an id for round participation
/training-data?id=	GET	Obtain training data for id
/training-labels?id=	GET	Obtain training labels for id

Figure 4: HTTP endpoints

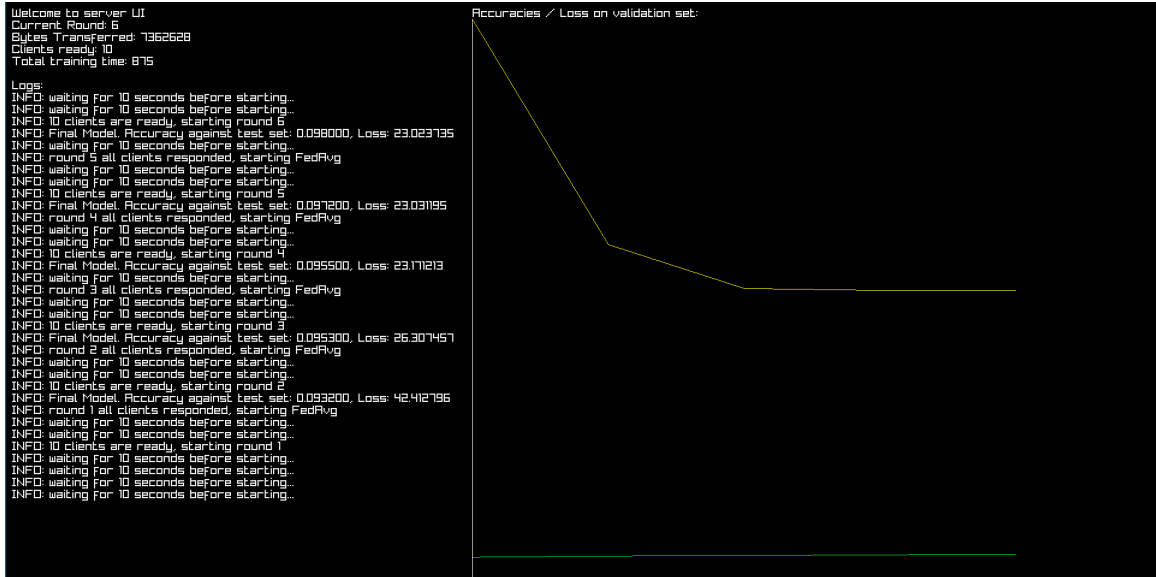


Figure 5: GUI Implementation

5 Experiments

The framework is tested using FedAvg over the MNIST digit recognition data set of 60000 labels. Due to memory constraints, clients are configured with a neural network architecture with 1 hidden layer of 16 nodes. Additionally, implementations for the softmax activation and cross entropy were made to ensure suitability for machine learning with MNIST categorical data.

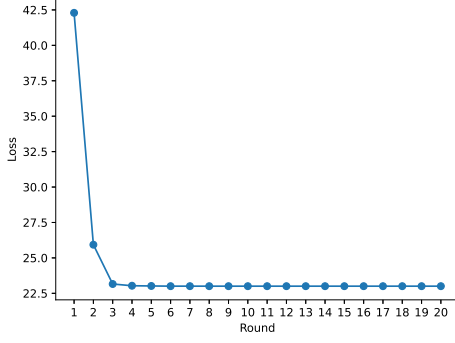
To test the sanity of the framework, the data is first shuffled and split equally into 100 sets of 6000 labels. The server is started for 20 rounds and 100 clients per round and clients were started with 5 epochs and a batch size of 600. Figure 6a shows the validation set loss and Figure 6b shows the validation set accuracy at the end of each round. There can be many reasons for the lack of accuracy gain. For one, the model architecture is very shallow, reducing each clients ability to make significant steps towards their local minima. Furthermore, traditional FedAvg also suffers from model inaccuracy caused by the loss of knowledge during model training[13]. Nevertheless, although the framework is unable to converge towards an acceptable target accuracy during the experiment, a steadily decreasing cross entropy loss helps to validate that the entire system is performing.

In addition, the same experiment is repeated with 10% packet loss emulation enabled. As described in section 4.3.2, Figure 7a, 7b, 7c, 7d plots the network statistics. As expected, packet loss results in greater number of TCP retransmissions. Wireshark[?] can also be used to capture packet information going through the network interface. Figure 7e depicts a plot of TCP packets per second over the time of the experiment using a logarithmic scale. The brown lines represent all good TCP packets while the red bars represent TCP errors. Figure 6c also depicts the training time.

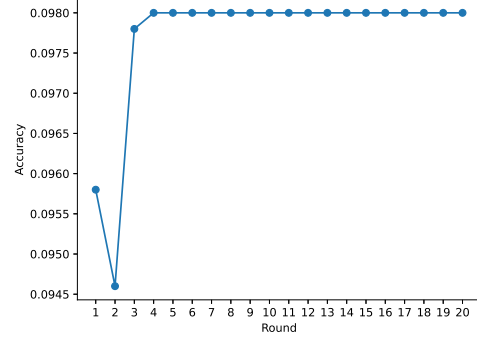
6 Limitations

6.1 Long training times

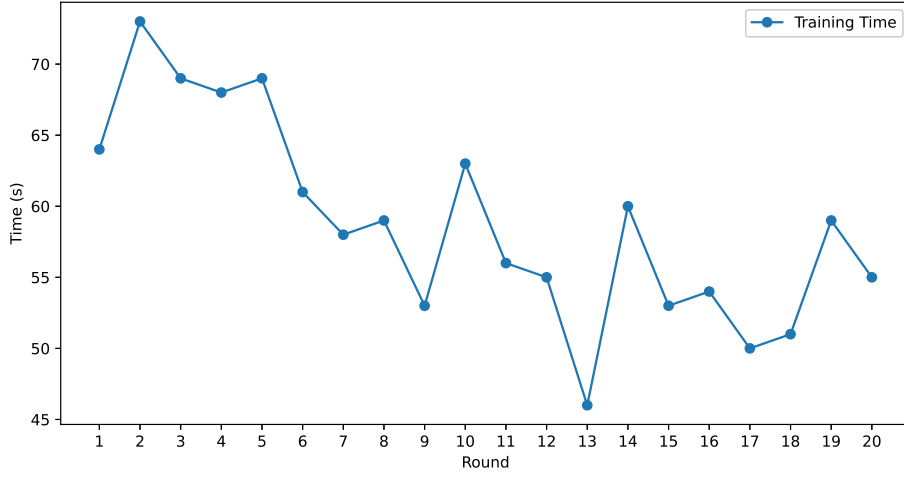
Unoptimized client training implementations has resulted in long training times required per FL round. This is because standard implementations for machine learning algorithms that can be easily ported and suitable for use in Zephyr OS could not be found. Traditional runtimes such as Tensorflow[14] rely on the availability of a Python interpreter on the device. Furthermore, these runtimes are



(a) Validation set loss



(b) Validation set accuracy

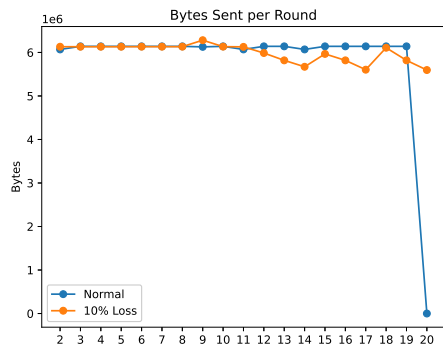


(c) Average Training Time

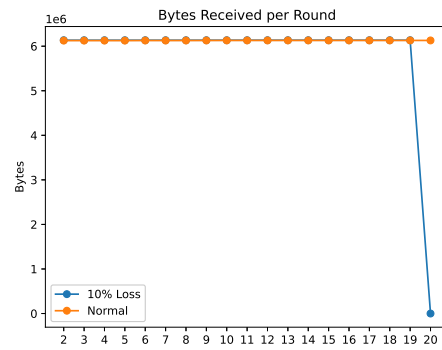
usually not developed or optimized for resource constrained environments, incurring a large binary size and high memory usage. However, there is progress towards integrating Tensorflow Lite Micro into Zephyr OS through external modules and has examples for running pre-trained neural network on their platform. However, on-device training is still not supported.

6.2 Limited algorithm support

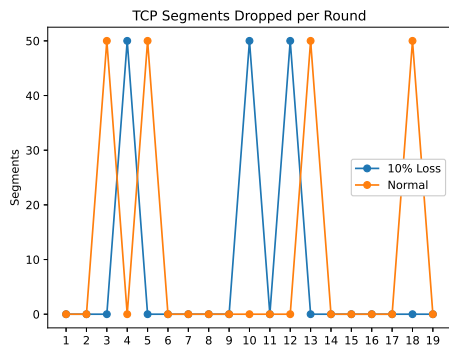
The framework currently only implements training algorithms for FedAvg. The architecture of `zfl` also inherently assumes the use of a single server instance used for aggregation. However, this limitation can be bypassed by porting specific HTTP endpoints from the server to the client. For example, the implementation of the `results` endpoint, would effectively move aggregation into each client instance. This could potentially allow the framework to support hierarchical FL



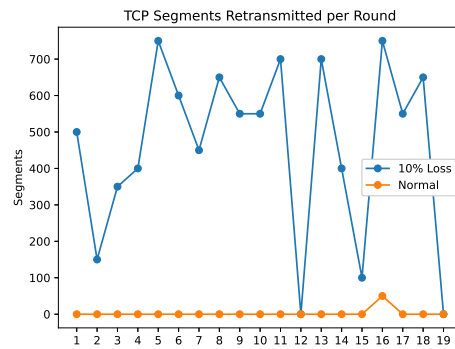
(a) Total Bytes Sent



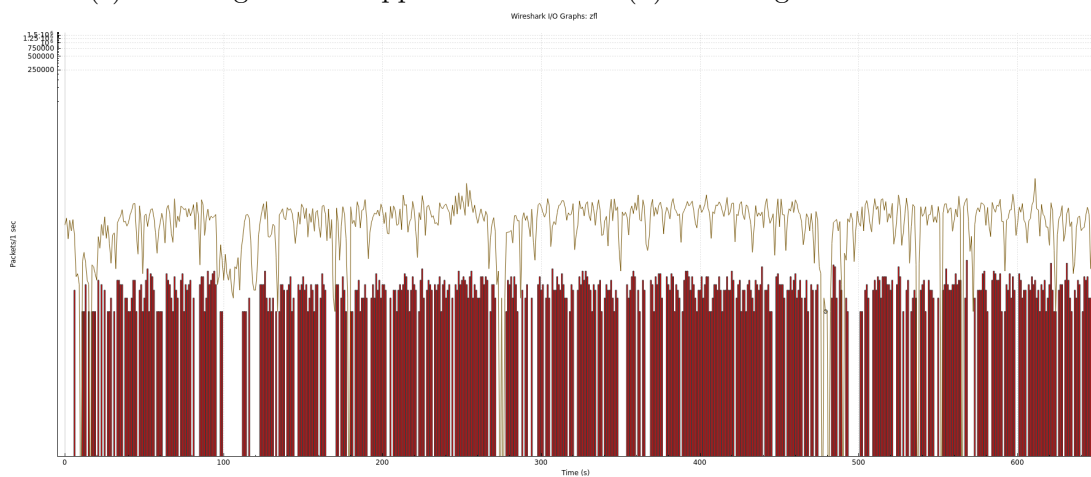
(b) Total Bytes Received



(c) TCP Segments Dropped



(d) TCP Segments Retransmitted



(e) Wireshark

algorithms[15].

Furthermore, future work could also look into implementing other FL algorithms in a bid to improve the usability of the framework. These algorithms should aim to achieve higher model accuracy without compromising on the requirements needed to function in an embedded low-powered device environment. One example could be Distillation Based Federated Learning[16].

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