Testing real-time containers for the cloud

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In this report a summary of the tasks performed during the short stay at UC Berkeley is given. This document contains a global summary of steps taken, tests done and options reviewed for the concept of application containerization to be run under real-time constrains in a computing cloud. The outcome of these tests will give insight in which might be the better configuration to run containers who rely on determinism in the cloud, and what influence hardware and software configurations may have. To better follow the execution order, chapters are listed in chronological order where possible, indicating approximate dates.

1 Introduction

This document is a report containing steps performed and outcomes obtained during the short visit at University of California at Berkeley. It is intended as a summary and, at the same time, a guideline if someone would like to repeat some, or all, of the tests.

The project team is composed as follows:

Alberto L. Sangiovanni-Vincentelli	UC Berkeley	Project Lead UCB
Antonio Iannopollo	UC Berkeley	UCB Project peer
Edward Kim	UC Berkeley	UCB Project peer
Juan Aparicio Ojea	Siemens USA	Team lead Siemens
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The description in this document resumes the work performed by the author of this report only. This document is not exhaustive and may be integrated in near future.

During my three weeks of stay, a weekly team meeting is planned (see Section 9) as well as daily informal sync at UC Berkeley.

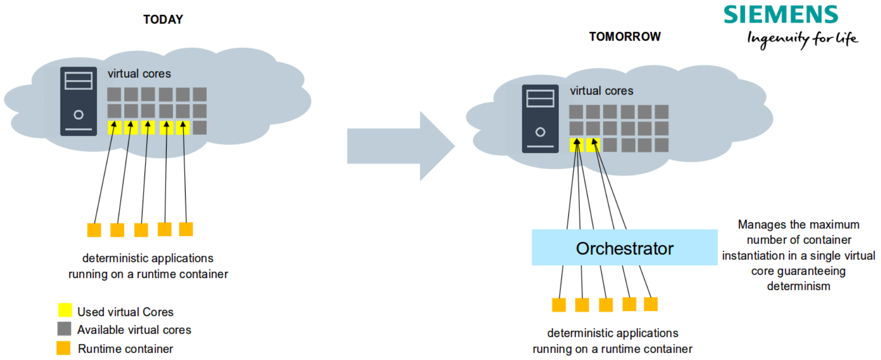

TODAY
virtual cores
deterministic applications running on a runtime container
Used virtual Cores
Available virtual cores
Runtime container
TOMORROW
SIEMENS
Ingenuity for life
virtual cores
Orchestrator
Manages the maximum number of container instantiation in a single virtual core guaranteeing determinism
deterministic applications running on a runtime container

Figure 1: Planned resource re-allocation

1.1 Background

The target of this short visit is to explore the possibilities for moving real-time applications into a virtualized context. In order to gain an insight in possibilities and limits of such an approach, a set of operating systems as well as system modifications are tried. The resulting configurations are then tested to verify their suitability to run a real-time capable containerization environment. If successful, this will allow a redistribution of applications onto a lower amount of resources. Figure 1 summarizes the foreseen future resource migration.

It is planned that this re-organization will save a major amount of resources, reducing the costs needed to operate the system, while still being appropriately deterministic. The software running on the system will be characterized by a set of real-time control applications.

There exist three categories of real-time applications: 1) soft, where the value of computation decreases as the deadline overshoot gets bigger, 2) firm, where the computation value of overshoots is zero, and 3) hard, where missed deadline may have catastrophic consequences [1]. According to Siemens, the target applications will have a period T of about $100ms$, where computing time is expected to be in the range of $\frac{1}{10}^{th}$. This means, to achieve hard-real-time operation and not miss any deadline, the application latency should never exceed $\frac{9}{10}^{th}$ of the period, i.e. $90ms$. If we have to run multiple applications on the same computing resources, the limits must be a fraction of the previous value. This makes $90ms$ application cycle execution delay an upper hard limit.

To isolate the different applications from one-another, a containerized approach has been chosen beforehand. The main choices available are LXC/LXD, Docker and Balena. LXC/LXD is the default Linux-based containerization engine. In its first release LXC was released as set of tools which are rather low level. The new extension LXD offers now a more intuitive approach, comparable to the more user-friendly Docker. LXC was rather difficult to use at first, probably one of the reasons why containerization did not take off until Docker came in. Docker is an open source project written in Go that was initially based on LXC technology, but has now moved on to directly use `libvirt`, a visualization library to access the dedicated kernel routines. It has centralized container image storage, an open API and easy to use CLI interface[1]. Balena on the other hand is a stripped down version of Docker which allows to minimize the resource requirements. It is thus also written in Go and available as open source project, hosted by resin.io. It uses the Docker infrastructure and has therefore a lot of its advantages while diminishing the load for the system. Balena kept most of the same configurations and parameters allowing a switch to Docker and its more advanced features at any time. For this reason, at the initial meeting of the 25-26/08/18 (see meetings in Section 9), Balena has been chosen as the containerization engine.

2 System Tests and variants

Identification of application candidates, 25-30/07/18

Before selecting a specific setup, different variants of systems are tested for their real-time capabilities, maintainability and ease of setup. Through some keyword browsing a list of potential systems has been identified. Candidates for this session are:

- **resinOS** operating system by *resin.io*, designed to run containers on different architectures and hardware devices. It has Balena pre-installed and features a cloud based interface to manage the different hosts and running containers.

- **Ubuntu Core** an operating system for IoT devices, implemented using the new snap image approach. Snap is a technology that takes advantages of containers and a package manager features (further explanation of Snaps in Section 2.2). Snap based as well as the easily installable Balena based solutions are investigated on this hardware optimized image

- **Xenomai 3** is a co-core extension for Linux based operating systems, which allows hard-real-time scheduling. Together with an interrupt pipeline patch, it is suggested to be the most performing of the real-time approaches.

- **PREEMPT_RT** a kernel patch for Linux-based systems which increments the achievable preemption level of the kernel. This allows for soft- and firm-real-time based performance, reaching hard-real-time on a properly tuned system

The lightweight CoreOS has been excluded from the candidate list as it comes pre-configured with a LXC/LXD container engine (LXC/LXD has been excluded beforehand). The systems are setup in separate virtual machines and are verified for real-time scheduling properties. The performed test installations will be used, also in future tests, to verify the run-time behavior of containerized applications of different kind, including synthetic applications.

[1] see [2] for a full list of features

2.1 resinOS by Resin.io

Test-run resinOS, 25/07/18

resinOS is an Project-Yocto based operating system designed by "resin.io" to run containerized applications on small systems. The design also includes a cloud based monitoring infrastructure where the different configured devices connect to. The default containers supplied by resinOS are based on the lightweight general purpose Alpine Linux distribution.

2.1.1 Local Virtual Machine

The resinOS operating system was primarily made to run on low resource hardware, embedded devices or alike, and does thus not have a specific image for desktop/laptop or server. To run the OS in a virtual machine we download the Intel based 64 bit image for the Intel NCU industrial unit from the resinOS website [3].

The image does not contain any additional configuration concerning network setup or ssh keys and thus by default is not possible to connect to the device. To configure the image we need the CLI tool. Before installing the tool, make sure that following packages are present and configured:

- **node.js 6.x** you can install the latest version via snap using *snap install node –classic –channel=x* where x can be substituted with the desired version, 8 or 10. You can also use a standard package installation. Instructions can be found at [4]
- **npm** the node package manager is part of the node distribution. If not yet installed, install it with *apt-get install npm*
- **rsync** versatile remote file copying tool, installable, if not already present, via *apt-get install rsync*
- **ssh** the secure shell client is usually pre-installed on all debian based systems. If that is not the case, install it via *apt-get install openssh-client*

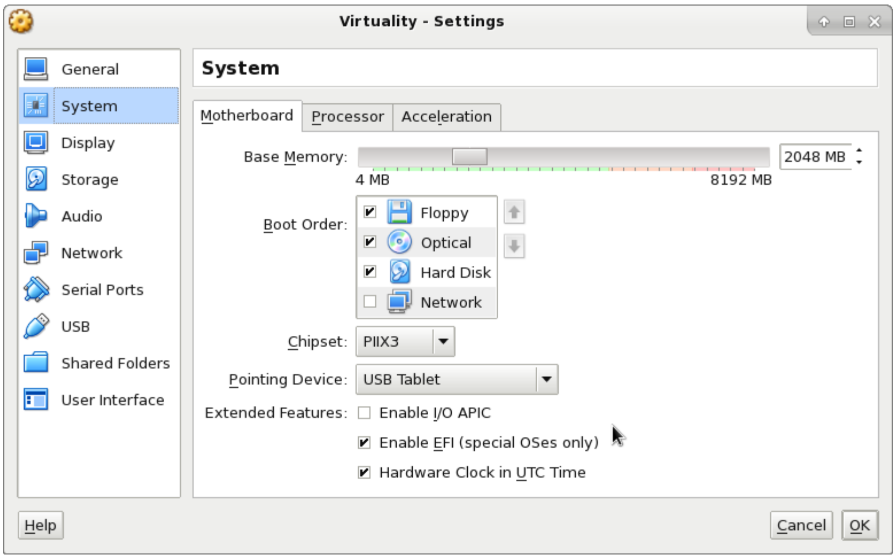
Once verified that all needed software is installed, the CLI tool for resin can be added using the node package manager. Please note the need of proper privileges (sudo).

```
npm install --global --production --unsafe-perm resin-cli
```

The CLI will now allow us to configure the image as needed. For a guided configuration, and assuming the downloaded image is in *Downloads*, type the following

Configure the image as needed

```
sudo resin local configure ~/Downloads/resin.img
```



Base Memory: 2048 MB

Boot Order:
☑ Floppy
☑ Optical
☑ Hard Disk
□ Network

Chipset: PIIX3

Pointing Device: USB Tablet

Extended Features:
□ Enable I/O APIC
☑ Enable EFI (special OSes only)
☑ Hardware Clock in UTC Time

Figure 2: Virtualbox general settings for resinOS

Manual configuration instructions and further details and documentation can be found at [5].

Before the image can be deployed to a virtual machine, it has to be converted to a virtual disk image. Use the Virtual-Box CLI tool to execute the conversion. Once switched to the folder where the image has been downloaded, type

```
VBoxManage convertdd resin.img resin.vdi
```

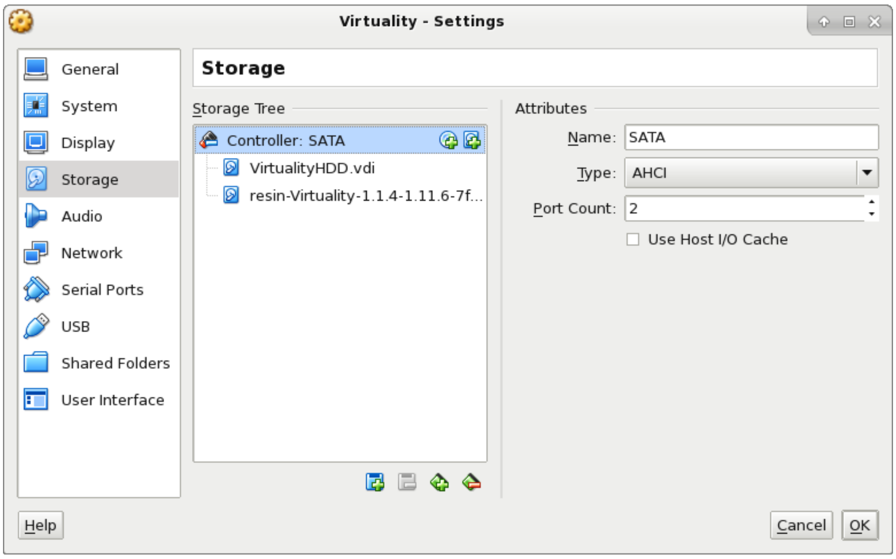
Next, create new virtual machine in Virtual-Box based on “Other Linux 64bit”. Minimum requirements are OK. Create a virtual Disk of Size of at least 4GB as main disk. When created, open the settings dialog for the virtual machine. In general settings, set the parameters as in Figure 2. Now add the boot image for resinOS in the storage menu, Figure 3.

To properly connect and download eventual containers we have to configure some port forwards. In the “Network” menu, select advanced, then Port forward. Configure now the forward of host port 8022 to client port 22 and host 2375 to client 2375, both for the client IP 10.0.2.15 (usually). The host IP can be left blank.

If the virtual machine is now started, the downloaded boot image creates a new instance of resinOS on the previously created virtual drive. The new disk is populated with the settings specified in the configuration step. Once done, the system shuts down automatically and the resin boot image can be removed from the machine settings. At next boot, the new virtual disk is used as boot image.

2.1.2 Run a Balena container in resinOS

As already discussed before, *resinOS* is shipped with Balena pre-installed and the system is now ready to run any desired container. An example application responding to a simple



Storage Tree:
- Controller: SATA
  - VirtualityHDD.vdi
  - resin-Virtuality-1.1.4-1.11.6-7f...

Attributes:
- Name: SATA
- Type: AHCI
- Port Count: 2
- ☐ Use Host I/O Cache

Figure 3: Disk settings for resinOS

web request can be set-up and tested with the following guide.

Clone the repository to a local directory with

```
git clone https://github.com/resin-io-playground/resinos-sample
```

Now enter the repository and edit “Dockerfile”. Replace the text after FROM with *resin/intel-nuc-alpine-node:slim*, to use the NUC intel image instead of an ARM version as base file. Now compile and upload the container to the virtual host with

```
sudo resin local push localhost --source .
```

Setup a route from the virtual machine to the local host, line before, from port 80 to port 8080. Browsing to `localhost:8080` should now display a test page.

2.1.3 Evaluation

The resinOS core ships with no packager manager and is missing building tools. This image can therefore be patched only manually and with greater effort. This also means that it increases the maintenance effort and makes thus a resinOS based approach unpractical. In addition, the image has been tuned for small devices' operation. An operation on a server infrastructure might therefore not use the maximum capabilities of the hardware, constraining the system in its performance.

2.2 Ubuntu Core

Test-run Ubuntu core, 25/07/18

Ubuntu Core is a project by Canonical intended to exploit the advantages of standard Ubuntu technology and run small and transactionally upgradeable applications on embedded devices. The developed application for the end device is shipped as a software package, a snap, and runs sand-boxed in a container-like environment while keeping the transparency of a traditional application.

Snaps are standard feature of Ubuntu based distributions since 2 years now. It combines the advantages of a package manager and an application container. Even though the snap itself runs on isolated resources provided through proper `cgroup` configuration, it maintains the accessibility and transparency a locally installed software would have. The running applications are practically sand-boxed, having separated partitions for binaries, application specific settings, and the actual file system of the host OS. The host and the binary partitions are read-only, protecting the hosting system from eventual malicious software. In addition, the binaries are digitally signed and thus tampering with the executable is avoided. This gives the whole system the flexibility of continuous updates of an application while being independent of the host system and flavor, and without interacting with the file system of the host. A variety of Linux flavors support snaps. In addition, snap-stores can be privately hosted, making this solution very interesting. More details can be found at [6]

In this test, a setup is described and feasibility of the candidate is verified.

2.2.1 Local Virtual machine

Like in the previous example, the image is downloaded and ready to be used. Visit [7] for an additional step-by-step guide. First, we get and unpack the latest KVM core image (replace version numbers where appropriate):

```
wget http://cdimage.ubuntu.com/ubuntu-core/16/stable/current/ubuntu-core-16-amd64.img.xz
unxz ubuntu-core-16-amd64.img.xz
```

Before it can be used for boot-up, the downloaded ISO image has to be converted from a raw image to a virtual drive. We convert the image again with the VirtualBox CLI tool.

```
VBoxManage convertdd ubuntu-core-16-amd64.img ubuntu-core-16-amd64.vdi
```

Now we create a new virtual machine based on “Ubuntu 64bit” and add the existing disk. The setup of the virtual machine is guided and therefore no additional description is given here. Standard settings are good enough. Once done, the system is ready to run.

In order to be able to connect to the new virtual machine we need a Ubuntu One account [8]. If you do not have one yet, sign up for a new free account. Once logged in, we have to configure and/or upload at least one ssh key we are going to use to connect to the core device. The booted device will ask the email of the Ubuntu One account and subsequently download all registered ssh keys. Finally, to connect via ssh we have to configure some forwards. In the settings, select “Network”, advanced, then Port forward.

Configure now the forward of port 8022 to 22 for client host 10.0.2.15 (usually), the same way as described for resinOS.

For a description on how to create a ssh key, visit [9]

2.2.2 Evaluation

Unfortunately, as for resinOS, also Ubuntu Core is stripped to minimum and ships with no packager manager and building tools. Therefore, the same conclusions as before apply.

Unfortunately, even though the snap feature is native to Ubuntu and a patched kernel could add the needed real-time properties, the binding with the hosts name and file-space hinders the use of application duplicates, i.e. running the same application multiple times with different configurations. This approach is thus archived for the moment.

2.3 Ubuntu Server 16.04.4 with Xenomai

Testrun Xenomai, 26/07/18

Xenomai is an OS extension which can be used to support POSIX real-time calls in a standard Linux kernel. Xenomai integrates it with Cobalt, a small real-time infrastructure which schedules time-critical activities independently of the main kernel logic. The interaction with an interrupt dispatcher (I-pipe) allows to increase response time and performance and thus enables also for hard-real-time execution. Through further extension with interface skins, also non POSIX compliant real-time software can be configured to run on a Xenomai patched system.

The main expressed concerns of this approach are setup complexity and maintainability.

2.3.1 Local Virtual machine

The base-OS should be lightweight but still fully featured. Thus, an Ubuntu server flavor with minimal installation has been chosen. Download the image from the Ubuntu website [10]. The latest patches available for Xenomai/I-Pipe are based on Kernel 4.9.x and 4.14.x. Ubuntu 16.04 is the closest version with 4.4.x as the next LTS, namely Ubuntu 18.04, is shipped with Kernel 4.15.x. Thus, we select Ubuntu Server 16.04.4 as the candidate for a kernel upgrade and patch.

```
# download image
wget http://releases.ubuntu.com/16.04.4/ubuntu-16.04.4-desktop-amd64.iso
# verify image hash
curl -sfL http://releases.ubuntu.com/16.04.4/SHA256SUMS
| sha256sum -c 2>&1 | grep OK
```

Next, we create a new Ubuntu 64bit based virtual machine with a disk size of at least 20GB. Even though Ubuntu takes just a few GB, we need at least 10GB extra space for the libraries, source code and compiling process of kernel image and header. The memory size for the virtual machine can be arbitrary chosen between 384 MB and inf. When setting the number of assigned CPUs, consider that, the more, the faster is the compiling of the new kernel (upper limit, of course, are the physical no of threads). If you increase the number of CPUs, increase also the amount of RAM. Before starting the machine, we add the Ubuntu server disk image to the CD drive of the new machine.

Now follow the guide of the installer. If asked, add only ssh server to the pre-selected packages and continue with software deployment. Once the installation is done, don't forget to upgrade the system to the newest packages and restart before proceeding with the kernel build. Execute the following in the freshly booted system:

```
apt-get update && apt-get dist-upgrade -y
```

The patching steps have all be resumed in an installer script by Pasquale Antonante. Unfortunately some steps are outdated and some configurations have changed. The script has therefore been updated and placed in the appropriate directory of this repository [11]. The install script provides automatic downloads of the two patches, Xenomai/Cobalt and I-Pipe, the kernel, performs the patch and installs new kernel and the Balena environment.

2.3.2 Evaluation

Because of the way interrupt handling is implemented, using out-of-band interrupt handlers and thus immediate IRQ reception, Xenomai is an ideal candidate for hard-real-time applications. The patching is bound to kernel versions, thus the progress depends on the patch development of I-Pipe. The scheduling of the real-time tasks is performed in the co-kernel and is thus easier to change, a promising approach. Currently the kernel patch development line (incomplete) is stuck at version 4.14.4. As a comparison, the latest kernel shipped with Ubuntu 16.04 LTS is 4.15.0-29 while the latest stable version is 4.17.11. This could be a sign of an abandoned project. Before continuing with this implementation line, a proper investigation of the project status and agenda must be performed.

2.4 Ubuntu Server 16.04.4 with patch RT

Testrun Preempt-RT, 27/07/18

PREEMPT_RT is a real-time kernel project maintained by the Linux foundation. The main aim of the PREEMPT_RT patch is to minimize the amount of kernel code that is non-preemptible. Therefore, several substitutions and new mechanisms are implemented. In the last years there were some major improvements in the PREEMPT-RT performance. A paper of Fayyad-Kazan *et al.* shows improvement on kernel versions v2.6.33 versus v3.6.6 of a total of 35% [12]. In order to keep performances and results comparable, preferably the same Ubuntu image as for Xenomai will be used for patching.

2.4.1 Local Virtual machine

The same conditions as in the previous example apply. Download the image from the Ubuntu website [10], if not already done. See section 2.3.1.

The patching steps have all be resumed in a newly created installer script similar to the previous case with Xenomai. The install script provides downloads of the patch and the kernel, performs and installs the patch and installs the Balena environment.

For further guides on how to compile and install a kernel, visit [13].

2.4.2 Evaluation

The Preempt-RT requires a dedicated patch, recompiling and tuning of the kernel to support hard-real-time properties. The additional slicing preformed to the kernel tasks allows faster preemption and a better control of the CPU scheduling. Compared to the previous example, the handling of interrupt flow can not be controlled to the same extend reaching thus a lower real-time guarantee. In particular, drivers must be tuned for real-time operation in order to reach low process firing jitter. Anyway, lately the project has made remarkable progress. Its mainline development is following kernel distribution at a fast pace, indicating that the project is strongly followed and has a valuable community backup (visible e.g. through events like [14]). This makes the solution a major candidate for further investigation. To exploit its full potential, patching of a newer kernel is taken into consideration as a future step.

3 Tests of system

Test-run and comparison of systems, 30/07/18

Some small cyclic execution tests are performed to verify default availability of real-time scheduling and the timing behavior of the system's scheduler. Some tools will be downloaded and installed to test for latencies, responsiveness and reaction under CPU stress.

3.1 rt-tests

The rt-tests suite includes a list of small tool binaries which may be used to test properties of real-time systems. The most known are *cyclictest* and *hackbench*. The former is used to create a number of real-time tasks executing periodically which then report their starting latencies. The latter has specific features to backtrack also single latencies (`--breaktrace`), allowing to debug the latency trace of the preemption kernel. It is a feature that requires a specific kernel configuration and might thus be used in a second moment, i.e. when configuring the container host OS. To install the software we may use one of the two approaches:

1) We use Xenomai 2.6.x (which is not our case), then there is a ready to go tool package available

```
apt-get install xenomai-system-tools
```

2) We use another version or real-time approach and compile the binaries from the source code. For this approach we need first some additional packages. Get them with: (**Note:** for Xenomai 3.x check new findings in Section 5.3 before continuing)

```
sudo apt-get install build-essential libnuma-dev
```

Now proceed with the installation. Download the git repository and compile the source.

```
git clone git://git.kernel.org/pub/scm/utils/rt-tests/rt-tests.git
cd rt-tests
git checkout stable/v1.0
make all
make install
```

The last step is optional. The binaries can now be run (within the directory) to perform the different tests. An example of a test recommended by Kernel.org is:

```
cyclictest -t 50 -n -d 86400 -l 100000 -a -p 99
```

The code in the example creates fifty tasks with priority 99 (maximum), an interval of 1000 μs, a task period distance of 86400 μs and is using a clock-based nanosecond timer. An interesting feature is the `-h` flag, which plots a histogram and the number of overshoots. The feature will be used in a second moment.

As an example, we compared the results between virtual machines of the different kinds we have set up by now. There is an improvement between normal and patched images, but the actual values are for now far from ideal. At the moment, as the host is not hard-real-time capable, the delays also depend on the task and resource scheduling of the host which runs the virtual machine. An eventual cloud based host OS used to manage the virutal instance will also not run a hard-real-time capable kernel by default. Thus, configuration and tweaking tests of a VM host could give some more comparison and reference data.

3.2 stress

In order to verify behavior also under stress we use the tool *stress*. The tool starts some random computation to put load on the virtual machine. The particular thing about stress is that, in addition to CPU load, it can also generate threads for memory allocations, I/O sync requests and disk stress on the target system. The installation can be performed by downloading and compiling the source code. Further information can be found at [15].

```
#download and extract
curl -sfL http://people.seas.harvard.edu/~apw/stress/stress-1.0.4.tar.gz | tar xvz
# compile and install
cd stress-1.0.4
./configure
sudo make install
```

An example execution starting three threads of each function of stress can be performed via the command:

```
stress -d 3 --hdd-bytes 20M -c 3 -i 3 -m 3 --vm-bytes 15M
```

A more advanced version, `stress-ng`, is also available. It features more tests and configuration options, and will be used for endurance tests in future work [16].

3.3 Other testing tools

A list of other tools that might be helpful:

- **htop** a colored memory view to analyse memory use of single processes
- **iftop** interface monitor to view actual network traffic
- **iotop** generic I/O monitor
- **nmon** a universal monitoring tool

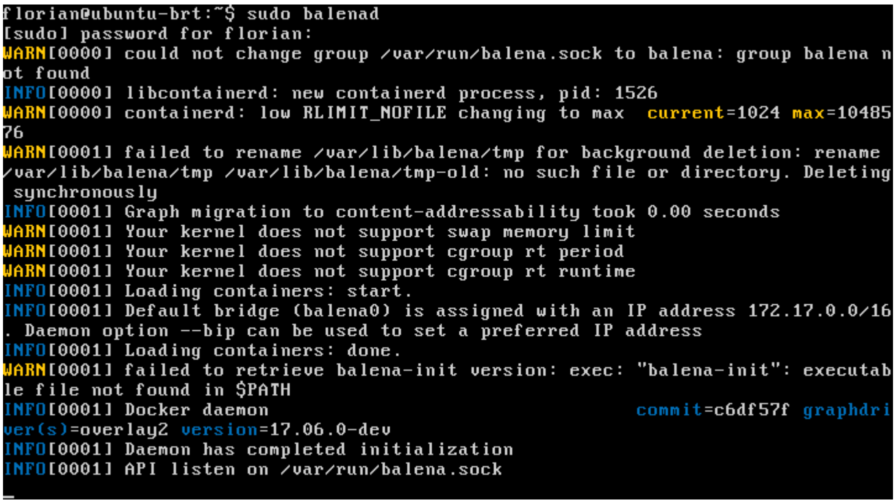
4 Additional fixes

Configuration test, 31/07/18

Balena, even though installed via the official script, appears not properly configured. It does not run at startup and there is no typical dedicated group in order to ease and limit access to the engine. Therefore, groups and systemd configuration files to manage these must be added manually. Use the Docker reference manual to provide for this. The manual can be found at [17]. The Balena daemon is started via the command *balenad*.

It is also unclear why the official installation script misses the `balena-init` file, see Figure 4. Comparing the installation to the standard resinOS shipping we can see that the latter has the mentioned file. The two Balena engines have the same version number, but interestingly the main binary of the tool is different. It is unclear what this might mean. The init binary is intended to initialize a newly created container in order to remove all the orphaned resources and prepare it for a clean run.

If we refer to documentation it just seems a forgotten installation step. According to the Docker reference manual, [18], the init binary for the standard Docker-based installations is obtained from the `tini` project, and can thus be safely pulled from there. The git repository can be found at [19].



```
florian@ubuntu-brt:~$ sudo balenad
[sudo] password for florian:
WARN[0000] could not change group /var/run/balena.sock to balena: group balena n
ot found
INFO[0000] libcontainerd: new containerd process, pid: 1526
WARN[0000] containerd: low RLIMIT_NOFILE changing to max  current=1024 max=10485
76
WARN[0001] failed to rename /var/lib/balena/tmp for background deletion: rename
/var/lib/balena/tmp /var/lib/balena/tmp-old: no such file or directory. Deleting
 synchronously
INFO[0001] Graph migration to content-addressability took 0.00 seconds
WARN[0001] Your kernel does not support swap memory limit
WARN[0001] Your kernel does not support cgroup rt period
WARN[0001] Your kernel does not support cgroup rt runtime
INFO[0001] Loading containers: start.
INFO[0001] Default bridge (balena0) is assigned with an IP address 172.17.0.0/16
. Daemon option --bip can be used to set a preferred IP address
INFO[0001] Loading containers: done.
WARN[0001] failed to retrieve balena-init version: exec: "balena-init": executab
le file not found in $PATH
INFO[0001] Docker daemon                                      commit=c6df57f graphdri
ver(s)=overlay2 version=17.06.0-dev
INFO[0001] Daemon has completed initialization
INFO[0001] API listen on /var/run/balena.sock
_
```

Figure 4: Error messages displayed by Balena at first run

Figure 4 shows also a number of further warnings. In particular, we can identify two groups of warnings:

- *WARN[0001] Your kernel does not support swap memory limit*
- *WARN[0001] Your kernel does not support cgroup rt period* and *WARN[0001] Your kernel does not support cgroup rt runtime*

The former is due to the fact that memory swap support has not been enabled at kernel built time. The configuration setting to be enabled is `#CONFIG_MEMCG_SWAP_ENABLED`. As a temporary fix we can enable the settings at boot-time. To do this we edit `/etc/default/grub` and set `GRUB_CMDLINE_LINUX_DEFAULT` to `"cgroup_enable=memory swapaccount=1"`

The latter of the two warning groups is also due to a configuration setting of the kernel. They concern the real-time run-time control of single cgroups. This is a feature which is needed/used in containers when we want to control a containers' maximum CPU execution slice, see [20]. In fact, if we try to set some real-time settings on our running Balena instance we get the following error message: *balena: Error response from daemon: Your kernel does not support cgroup cpu real-time runtime.*. The required setting can be enabled at kernel compilation time via the `CONFIG_RT_CGROUP` flag. Unfortunately the flag can not be enabled for the PREEMPT_RT version of the virtual machine. Due to some temporary compatibility constraints, the simultaneous operation of the `CONFIG_PREEMPT_FULL` flag, necessary for the ability of full kernel preemption, and the CGroup flag has been disabled. Details can be found at [21].

Finally, I found a script that could do the verification for you. If you would like to test your system for parameter and capability compliance, the Docker community has developed a configuration testing script. The test can be run via these inputs:

```
wget https://raw.githubusercontent.com/dotcloud/docker/master/contrib/check-config.sh
```

```
chmod +x check-config.sh
./check-config.sh
```

The run of the script confirms that the Xenomai version of the image, after all reconfiguration and recompilation, has the correct settings to operate the container engine with real-time features.

5 Virtualization sustainability tests

Test-run Containers & CPU pinning, 01/08 - 03/08/18

In this section we verify the expected latencies of real-time tasks in different settings. In order to do this, a variety of system configurations are performed and capabilities verified. The list of all capabilities can be viewed on every Linux based system by typing `man 7 capabilities` into a shell. As we have seen in the previous section, the Xenomai image supports all the real-time features needed for Balena. Thus it has been selected as guest OS for the following tests. These tests should give an insight how a real-time container and/or application will behave when put into a virtualized environment like the Amazon AWS cloud. Amazon offers different setups, from shared or dedicated virtualized hosts to bare metal applications. Thus, in our tests we try to identify parameters for two running options: 1) shared virtualized instance, where a hyper-visor controls the whole instance, and 2) a bare metal server, without hyper-visor and running our preferred hard-real-time capable OS. The results will show how the set-up and configuration of a hyper-visor running a guest OS in the computing cloud, here the Host, could influence latencies and responsiveness of a real-time application running in a virtualized environment.

During some additional research on Balena and its relation to Docker, the source code of Balena actually revealed that Balena exposes the same API. Thus, the use and parameters for compose, namely `docker-compose`, is available to run also on a Balena based system. `docker-compose` is a tool written in python which allows to configure and connect multiple containers remotely using a single Json file, a welcome feature for our project. Anyway, by the source code of Balena we can tell that not all the tags are supported. This is particularly valid for the 'Deploy' section.

More detail on the different activities performed in this section and on why those are performed, can be found at [22].

5.1 Preparing steps

In preparation for the upcoming tests we need to install `docker-compose`. The instructions can be found in the reference of Docker, see [23]. On Debian systems this can be done simply via

```
apt-get install docker-compose
```

In the settings of the virtual machine we set the CPUs to three, and we start the virtual machine.

5.2 CPU isolation and partitioning tests

Let us try to start with some first measurements. We will run the tool `cyclictest` in different combinations, with and without stress on the CPU. During the test, we will use two versions, one with system load generated through the tool `stress` and one without. The `-q` flag on the `cyclictest` program is mandatory because if on-line, it continues to overwrite the values which could result in shifted, bigger looking results. The goal of this test is to find a configuration that permits a very low average and peak latency and thus relatively the best performance in a vitualized environment.

```
#Test without load
cyclictest -n -a -m -q -p 99 -l 100000
#Test with system load
stress -d 3 --hdd-bytes 20M -c 3 -i 3 -m 3 --vm-bytes 15M &
 cyclictest -n -a -m -q -p 99 -l 100000;
```

The specified options for `cyclictest` are: nanosecond clock timer (-n), set CPU affinity thus no rescheduling of test threads (-a), lock memory allocations (-m), quiet run (-q), real-time priority 99 - maximum (-p 99), loop count 100000 (-l 100000).

The measurement result are then printed with the following schema

```
T: 0 (<pid>) P:<p> I: <i> C: <c> Min:  <n> Act:  <a> Avg:  <v> Max:  <x>
```

Where:

$pid =$ threads PID,
$p =$ threads real-time priority,
$i =$ execution interval in μs,
$c =$ cycle count of execution
$n =$ min run delay in μs,
$a =$ last cycle's run delay in μs,
$v =$ average run delay in μs,
$x =$ max run delay in μs.

Tests will be repeated to confirm values also in different situations.

5.2.1 First tests with host

First of all, let us get some base measurements. The testing host is a dual core, 4 thread, sixth generation i7 Skylake (U) system with 16GB of RAM. The guest has been set-up to three cores and started without any further change. Ultra-books and laptops often disable Hyper-threading to save energy when operating on battery (a power management setting). Thus, in order to have all threads running, plug-in the power cable before continuing. In addition, in many cases the *cpu-governor* controls the bus frequency even if plugged in. Thus, we change the governor settings running the following as root.

```
cpupower frequency-set -g performance
```

Now the clock frequency should be locked between upper limit and turbo frequency (where available). Frequencies can be verified with `lscpu`.

The cores are all enabled and the system is ready to perform. We begin thus with the first two tests:

No load :

```
#1 T: 0 ( 1489) P:99 I:1000 C: 109551 Min:  0 Act:  4894 Avg:  1370 Max:  491481
#2 T: 0 ( 1687) P:99 I:1000 C: 100000 Min:  0 Act:  186 Avg:  1877 Max:  818579
#3 T: 0 ( 1689) P:99 I:1000 C: 100000 Min:  0 Act:  604 Avg:  1664 Max:  892794
```

Load (stress):

```
#1 T: 0 ( 1731) P:99 I:1000 C: 100000 Min:  1 Act:  40 Avg:  311 Max:  11892
#2 T: 0 ( 1748) P:99 I:1000 C: 100000 Min:  1 Act:  85 Avg:  292 Max:  27666
#3 T: 0 ( 1765) P:99 I:1000 C: 100000 Min:  1 Act:  413 Avg:  290 Max:  11818
```

The first values obtained without load show very high peak values (Max) and average delays (Avg) bigger than the loop cycle times. On the other hand, the `stress`ed run has a lower peak and delay times, way lower than the cycle time. That is probably due to the continuous movement of tasks on different CPUs in the first case. The low load allows the scheduler to fill up the available CPU time with other threads, and thus, also to distribute them (load balance) between the CPUs. This movement of tasks causes the CPU registers to be flushed and L1-L2 caches will have to be refilled from the L3 cache. All these actions introduce latencies which are visible in the average and peak values. The guest under stress does not allow very much free CPU-time on the physical CPUs. Thus, the host's treads are mostly run on the CPU not serving any of the virtual machine's threads. Finally, this prevents the scheduler from shifting of threads to other CPUs and avoids thus resulting added latency. A direct consequence is that, even though the load on the system is higher, the overall performance is better.

A conclusion that might be drawn from this is that, if the virtual guest in the cloud is run on shared physical CPUs, a similar scenario might occur. The standard Amazon AWS instance uses a Complete Fair Scheduler (CFS), the same type of scheduler used for standard Linux threads in our testing host [24]. Therefore, in such case, either the resources for the virtual machine are all allocated to a reasonable extent with real-time applications, or the system might require some added stress, like in this test, to force the host scheduler into a more predicable behavior.

5.2.2 Working with host CPU isolation

CGroups is a standard Linux feature used for resource partitioning and CPU pinning (affinity selection). It is one of the techniques also used by Balena & Co. to isolate the containers from the host. It is a technique that might be used in combination with previous systems in order to increase their real-time properties. The tool *cpuset* allows to perform a lot of the manual steps needed in an easier manner. Thus, in order to give the virtual machine proper computing power, isolate it from the host processes, and to allow isolation of the real-time tasks from non real-time processes, we will now set up CPU isolation for the host CPU. This change should bring the behaviour of the virtual guest closer to an actual AWS instance. In a AWS system, the hosts threads are usually not mixed with the clients threads, although in a best effort setting the physical CPU might be shared with another virtual instance. In the latter case, the considerations taken in the previous section might become useful again.

A two core machine will usually have four CPUs, meaning two cores and two threads per core which equals 4. Thus, we will assign CPUs 0-2 to the virtual guest and CPU 3 for the host system. In general, throughout this text we will distinguish between pCPU, the physical

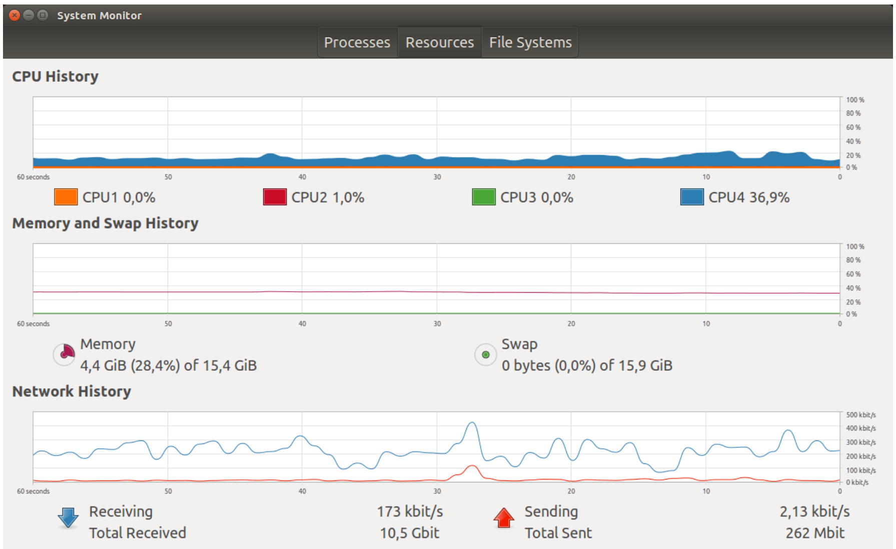


Figure 5: System monitor showing the isolated virtual machine (idle, CPU 1-2-3) and the loaded hostOS dedicated CPU (CPU 4)

amount of available CPU units, vCPU, a virtual CPU in a VM instance, and CPU seen as the computational units identified by Linux, i.e. pCPUs times the possible computation threads per pCPU, or CPU Cores x 2 for hyperthreading enabled units. The maximum vCPU count is usually determined by the number of available computation threads, thus CPUs.

First of all we need to install the `cpuset` utility on the host system. This can be done via:

```
apt-get install cpuset
```

Next we set-up the CPU-isolation. Open a process monitor, e.g. the system monitor, and get the PID of the running virtual host. Open a shell and change to root (or use sudo):

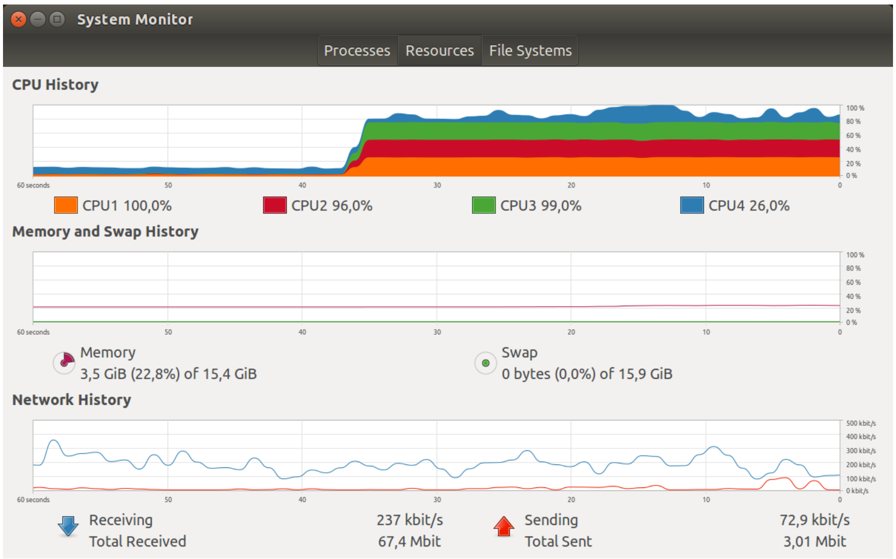
```
cset shield -c 0-2 -k on --shield &&
cset shield --shield --threads --pid <read-pid,read-pid>
```

The virtual machine and all tasks depending on it are now moved to a separate control group named `user`, which has exclusive access to the CPUs 0 to 2. All tasks of the host, where possible, have been moved to CPU 3 in the new group `system` (verify with `cset shield --shield -v` and `cset shield --unshield -v`). In Figure 5 the effect on the host of CPU-isolation is shown.

Results with CPU isolation:

```
#1 T: 0 ( 1431) P:99 I:1000 C: 100000 Min:  0 Act:  263 Avg:  1319 Max:  761816
#2 T: 0 ( 1615) P:99 I:1000 C: 100000 Min:  1 Act: 4387 Avg:  9382 Max:  1102853
#3 T: 0 ( 1710) P:99 I:1000 C: 100000 Min:  1 Act:  156 Avg:  5043 Max:  976019
```

With isolation, and still running a single real-time thread, the average delay is in some cases almost ten times the cycle time, causing the test duration to shift from planned 100 seconds to over 16 minutes. The values are very different and seem to vary based on the system load.



🟧 CPU1 100,0% 🟥 CPU2 96,0% 🟩 CPU3 99,0% 🟦 CPU4 26,0%

Memory
3,5 GiB (22,8%) of 15,4 GiB

Swap
0 bytes (0,0%) of 15,9 GiB

Receiving 237 kbit/s
Total Received 67,4 Mbit

Sending 72,9 kbit/s
Total Sent 3,01 Mbit

Figure 6: System monitor showing the same isolated virtual machine under load

One reason could be that, even though CPU affinity is set as parameter in the test, load balancing is still active. The host does not see the internal affinity settings of the virtualized guest, but only some threads to be executed. Thus, the test-thread could be shifted on the host OS level onto other CPUs to keep the average workload balanced. This is the same case as before where the CFS tries to distribute running tasks equally among the available CPUs.

Thus, in this second test, let us put again the virtual machine under load. If the previous theory is correct, an improvement on average and max values should be seen. The system's CPU load can be seen in Figure 6. It is as expected balanced on the three CPUs dedicated to the virtual guest.

Results with added load:

```
#1 T: 0 ( 1358) P:99 I:1000 C: 100000 Min:  0 Act:  49 Avg:  337 Max:  23395
#2 T: 0 ( 2364) P:99 I:1000 C: 100000 Min:  2 Act:  201 Avg:  348 Max:  17171
#3 T: 0 ( 2470) P:99 I:1000 C: 100000 Min:  1 Act:  38 Avg:  319 Max:  13496
```

And, as expected, the average dropped way below one millisecond, confirming the previous theory. Even though the threads of the virtual machine are confined on the tree CPUs, the load balancer of on the host is still active. We test now what happens when we deactivate the load balancer on the host:

```
#Removing load balancer total
echo 0 > /sys/fs/cgroup/cpuset/cpuset.sched_load_balance
#Removing load balancer shielded group
echo 0 > /sys/fs/cgroup/cpuset/user/cpuset.sched_load_balance
#keep load balancer system group
echo 1 > /sys/fs/cgroup/cpuset/system/cpuset.sched_load_balance
```

Results without load balancer:

```
#1 T: 0 ( 1643) P:99 I:1000 C: 100000 Min:  1 Act:  345 Avg:  8740 Max:  968040
#2 T: 0 ( 1805) P:99 I:1000 C: 100000 Min:  0 Act:  3004 Avg:  1705 Max:  792388
```

```
#3 T: 0 ( 2096) P:99 I:1000 C: 100000 Min:  1 Act:  88 Avg:  6960 Max:  894669
```

As we can see from the results, the values with and without load balancer did not change much. At the moment it is unclear why this happens. For now, let us continue with the tests.

For now only the tasks, user or system, have been moved from their original CPU to CPU 3. Interrupts on a multi-core system can be triggered on every active core and handled by the the specific routine. If our core serving the real-time thread has to serve the interrupt, the task has to wait.

In this next test we will move all possible interrupts to the last core. This should reduce the waiting time for the real-time tasks to be fired. It is true that every system will always have some IRQ requests during run, but in this test we are trying ro reduce the effect of the hosts system interrupts to the virtualized tests. On average, a slight improvement of the measurements should be visible. Thus, to isolate further, the virtual machine and move the IRQs only to CPU 3 we can use the following command:

```
# move irq affinity to Cpu 3
for file in /proc/irq/*; do   echo 8 > \$file/smp_affinity; done
echo 8 > /proc/irq/default_smp_affinity
```

The new test-results with moved IRQ affinity are then as follows:

```
#1 T: 0 ( 2151) P:99 I:1000 C: 100000 Min:  0 Act:  3481 Avg:  6496 Max:  892712
#2 T: 0 ( 1625) P:99 I:1000 C: 100000 Min:  1 Act:  3294 Avg:  9001 Max:  933678
#3 T: 0 ( 1966) P:99 I:1000 C: 100000 Min:  0 Act:  5380 Avg:  6599 Max:  928789
```

Unexpectedly, the values continue to move in the range of multiples of the cycle-time. Other tests that now can be performed is to enforce the isolation even more. Until now we used the tool `cpuset`, which isolates CPUs from their threads and gives exclusivity of access to certain processing units only to threads that have been assigned to them. Now we will restart the cores (via the hot-plug feature of the kernel) to force moving of tasks and IRQs to the other cores. We will use the procedure described in [25].

Following the description two things where noticed: 1) it is not possible to hot-plug the CPU0 and 2) disabling CPU1 disables also CPU2 and CPU3. While the former may be a convention in order to avoid disabling all CPUs, sometimes based on hardware [26], the latter is an actual misbehavior. When checking interrupt counters via `cat /proc/interrupts`, only vCPU1 is missing in the CPU list and IRQ reassignment seems not to work properly. Anyway, the problem looks to be isolated to some software bug and is not always reproduceable. Other CPUs hot-plug function worked properly. Thus, in order to be able to work with the instructions as of [26], the reserved CPUs will now be moved at the end of the range.

The interrupt table gives us also some other information: in the virtual guest, almost all interrupts between 0 and 22 are allocated on vCPU2, the last of the available vCPUs. This requires further investigation and is detailed in the next subsection.

5.3 Problem isolation and repetition

Unplanned review of results, 11/08 - 12/08/18

Investigating the IRQ allocation in the Xenomai 3 version of the virtual machine, and comparing it to a standard machine, the allocation is completely different. This could explain the unexpected test results.

If we consider a single test thread that is run manually multiple times, on average only one out of three threads will run on the same vCPU. As a test, if we try to pin the thread to the last

CPU, the one which has the highest interrupt count, we get the following results: (Task pinning has been performed with `taskset -p 8 <pid-no>`, i.e. it will always run on the last vCPU)

```
T: 0 ( 1695) P:99 I:1000 C: 100000 Min:  0 Act:  73 Avg:  148 Max:  4773
```

Interestingly, if we now deploy a thread on each vCPU, including the last one, we get a very close result, but still worse than the single thread on the last core. This is reproduce-able also by changing the number of CPUs and the vCPUs assigned to the virtual machine. Only if we include the last one, or we pin on the last vCPU, we get an average performance under one millisecond. This phenomenon needs further investigation.

Working through the documentation again, it is described how code must be implemented and build with Xenomai libraries in mind. This means that for Xenomai to work properly, **all real-time code must be recompiled** with the proper libraries, `cyclictest` included. Unfortunately this means, that all tests up-to now have been executed as soft-realtime Linux applications using the standard Linux kernel functions and not in the Xenomai space.

The following must be included before compiling again the files in the rt-test repository: in line 5 of the *Makefile* add [2]

```
XENO_CONFIG := /usr/xenomai/bin/xeno-config
CFLAGS := $(shell $(XENO_CONFIG) --cobalt --cflags)
LDFLAGS := $(shell $(XENO_CONFIG) --cobalt --ldflags)
CC := $(shell $(XENO_CONFIG) --cc)
```

If we run a test and verify the scheduled tasks with `cat /proc/xenomai/sched/threads`, we will see `cyclictest` listed as real-time application running in the cobalt scheduler. Naturally, now all the tests have to be repeated with the recompiled file.

To confirm our conclusions, we use another tool called `latency`, part of the Xenomai library suite. First we perform a free-run test, then a test without load balancer on the host, and finally we move the IRQ affinity to the host-only CPU the same way described before. The results are displayed in table 1. The tool can be found in `/usr/xenomai/bin` and has to be run with the parameter `-p 1000` to set the period to 1ms (value of cyclictest).

Table 1: Running results using the latency tool. All latency values are in μs

Description	lat. min	lat. avg	lat. max	overrun	runtime
1C	-1.389	190.744	13008.966	10782	00:24:13/00:24:13
2C	-4.194	14028.789	488841.139	1100418	00:20:22/00:20:22
2C iso	0.715	17216.756	495533.945	1759521	00:31:30/00:31:30
2C iso nlb	2.135	19644.141	239365.520	901520	00:16:14/00:16:14
2C iso nlb irq	0.716	21618.794	492396.514	2114650	00:37:27/00:37:27
2C aff	-3.681	212.699	288657.832	5882	00:19:17/00:19:17
2C iso aff	-1.627	210.960	7560.749	1685	00:14:25/00:14:25
2C iso nlb aff	-4.190	219.501	4843.218	3899	00:14:35/00:14:35
2C iso nlb irq aff	0.339	174.257	5064.610	4476	00:14:44/00:14:44

[2] Update: In a discussion thread I found that in the source code of cyclictest for Xenomai, the `sched_setsched` invocation to update the priority of a thread has to be replaced with `pthread_setschedparam` to properly set it for RT-tasks. The paper test have been updated accordingly

The description in Table 1 indicates the number of vCPUS (C), if CPU shield was active (iso), no load balancer set (nlb), IRQ affinity re-configured (irq) or cpu execution affinity to the last vCPU was set (aff).

5.3.1 Conclusions - isolation Host

We have seen in this first validation results that a VirtualBox task can be pinned to a certain CPU-set. Anyway, the results of the reaction times are varying with unclear reasons. One main reason could be that each one of the CPUs is not actually a separate core but only one of the two threads of the Hyper-threading instance of one physical core. Thus, it is possible that the increase in the max latency is due to the interrupt overload on the shared physical CPU, influencing thus directly the maximum performance and average latency of the real-time tasks. In addition, as discussed in the VirtualBox Forum `https://forums.virtualbox.org/viewtopic.php?f=7&t=82721`, it is not possible to pin the single threads representing a vCPU to a physical CPU, even if shielded. It seems to be a situation isolated to the implementation of the standard VirtualBox hypervisor.

The virtual machine in our example uses KVM paravirualizzation, the default setting for Linux in VirtualBox. KVM is a hypervisor which is actually supporting vCPU pinning. It might be thus possible to reconfigure the hypervisor by overriding VirtualBox settings to finally allow the thread pinning and avoid the CFS scheduler of the hypervisor to shuffle the vCPU threads. In any case, further tests with hypervisors such as native KVM hypervisor supporting this feature is advised.

The results of the `latency` tool are very similar to the initial tests performed with `cyclictest`. With average values in the range of ten milliseconds and peaks up-to one second, the values are not yet good enough. Anyway, considering the test setup and constraints, and considering the application requirements, we can safely state that running applications with a 90ms admissible latency **is** possible. The load tests did show peak values under 30ms, a third of the maximum allowance. Thus, what is now to improve is the idle response time of the visualized instance. Single or not properly distributed threads reached max lantencies over one second, ten times more than allowed by the application. How much improvement is actually possible and what the various options will be matter of future work.

For the sake of completion, the tests will be continued using the same concepts of isolation also for the guest.

5.3.2 Working with guest CPU isolation

We now try to set-up the same isolation concept also for the virtual guest. The available cores are separated into real-time (RT) and non-real-time (nRT) groups. We will use one full physical core, 2 vCPUs, for RT and one virtualization thread, or one vCPU, for the nRT tasks such as standard operating system tasks. This way we can completely isolate the RT tasks on a separate core. The installation of the software `cpuset` is required like in the host case. We now shield and start the RT task in an isolated CPU group.
Command :

```
# run shielding
cset shield -c 0-1 -k on --shield
# start test
cyclictest -n -a -m -q -p 99 -l 100000
# enable shield on test pid
cset shield --shield --threads --pid <cycletest pid>
```

```
# variant run shielded command
cset shield --exec --threads -- cyclictest -n -a -m -q -p 99 -l 100000
```

Results with CPU-isolation guest, no load balancer & IRQ affinity set on host:

```
#1 T: 0 ( 1664) P:99 I:1000 C: 100000 Min:  0 Act:  3037 Avg:  1913 Max:  201188
#2 T: 0 ( 2467) P:99 I:1000 C: 100000 Min:  0 Act:  4018 Avg:  1032 Max:  10262
#3 T: 0 ( 1832) P:99 I:1000 C: 100000 Min:  0 Act:  3413 Avg:  222 Max:  201796
#4 T: 0 ( 1835) P:99 I:1000 C: 100000 Min:  8 Act:  836 Avg:11725 Max:  718944
#5 T: 0 ( 1869) P:99 I:1000 C: 100000 Min:  5 Act:  39 Avg:  222 Max:  199000
#6 T: 0 ( 2243) P:99 I:1000 C: 100000 Min:  0 Act:  23 Avg:  158 Max:  200210
#7 T: 0 ( 2246) P:99 I:1000 C: 100000 Min:  8 Act:  32 Avg:12487 Max:  674647
#8 T: 0 ( 2257) P:99 I:1000 C: 100000 Min:  8 Act:10152 Avg:11605 Max:  765366
```

In the results we can actually notice when the task is running on the last vCPU (chosen by the scheduler in round robin) or not. The tests with averages under one millisecond have actually been found to run again on the last vCPU.

After we put load balance and IRQ affinity settings of the host back to normal, keeping CPU isolation we get the following results:

Results with CPU-isolation guest, load balancer and IRQ back in place for host:

```
#1 T: 0 ( 1912) P:99 I:1000 C: 100000 Min:  8 Act:  1898 Avg:14618 Max:  838961
#2 T: 0 ( 1924) P:99 I:1000 C: 100000 Min:  8 Act:  9826 Avg:14524 Max:  847310
#3 T: 0 ( 1934) P:99 I:1000 C: 100000 Min:  8 Act:  9569 Avg:14566 Max:  844467
```

The test shows that isolation on the host actually influences the latency test in the guest. Now, in addition we set the load balancer and IRQ affinity ion the guest to see if the performance improves. Remember to use value 4 this time for CPU affinity of the IRQs.

Results :

```
#1 T: 0 ( 1974) P:99 I:1000 C: 100000 Min:  8 Act:  9565 Avg:15748 Max:  858912
#2 T: 0 ( 1979) P:99 I:1000 C: 100000 Min:  8 Act:  9638 Avg:13784 Max:  826807
#3 T: 0 ( 2047) P:99 I:1000 C: 100000 Min:  5 Act:39152 Avg:13109 Max:  845584
```

Even after changing load balancer and IRQ affinity settings the values remain in the same range. It seems that the CPU isolation and configuration of the guest settings either has no impact or worsens the performance. Thus, for the moment, the shielding and isolation of resources in the guest system will not be considered. Anyway, some final tests with a dedicated server should be performed to confirm this conclusion.

5.4 Full dynamic ticks

A thing not evaluated yet are full dynamic ticks (see [25]). To achieve full dynamic ticks on a CPU, there are some requirements on the application being run on this CPU. First of all, it must not run more than one thread on each CPU. The use of POSIX timers is also not allowed, directly or indirectly, which means that no kernel calls that require such timers, i.e. network access, and many others. Thus keeping the kernel calls at a minimum at the application itself increases the probability that a full dynamic tick system is achieved. Second, the application must utilize the CPU partitioning, with e.g. `cset` done in previous section. After this, the shell command `taskset` can be used to bind the task to a specific CPU (task affinity) in the RT partition.

Anyway, by just by specifying "more than one thread on each CPU" we can exclude this approach upfront. We want to have more than one real-time application per CPU in order to save resources, thus, this configuration option is discarded.

5.5 Tests Balena container

Studying the Balena/Docker manual it was possible to identify the parameters to use in order to run the daemon with real-time capabilities. The parameter `--cpu-rt-runtime=<value>` enables the RT-sheduler for the daemon, set it to `-1` for no limit. In additon, for each RT-container `--cap-add=sys_nice` must be set, while `--cpu-rt-runtime=<value>` and `--ulimit rtprio=<value>` can be used to limit run-time and priority for each container respectively. More info at [27]

By default, the daemon listens to the sock file only. To change this, and thus allow external access, we can specify the connecting interface where to listen to with `-H`. By default a virtual host has an IP address of `10.0.2.15`. To enable the debug mode, we can add the `-D` flag.

To start the daemon in real-time mode thus we use:

```
balenad -H 0.0.0.0:2375 -H 10.0.2.15:2375 --cpu-rt-runtime=-1
```

where 0.0.0.0:2375 stands for the default sock connection. Before we can connect from outside we have to add the usual port forward to the client IP 10.0.2.15 and port 2375 on both sides.

We can now run a test container with the real-time test program using the container setup in test-cont folder. The container has been setup creating a standard Dockerfile and a `docker-compose` file where the needed parameters are set. To upload the container do the machine, change into the container folder and type:

```
DOCKER\_API\_VERSION=1.22 DOCKER\_HOST=tcp://localhost:2375 docker-compose up
```

docker-compose will now take care of downloading, building and running the image on the host.

docker-compose foresees to specify a parent cgroup for each container. This means that we can group containers into resource blocks and then assign CPU, memory nodes and RT-runtime for each set of containers. The parameters can either be changed via docker-compose file, the Docker command line or the standard cgroup virtual file system. An example of a run-time change for the main container root is the virtual file `/sys/fs/cgroup/cpu,cpuacct/docker/cpu.rt_runtime_us`. The parameters of a child can not exceed the value of a parent. **Warning**, misconfiguration can severely destabilize a system. Generic information about real-time group scheduling can be found at [28].

6 Final considerations, Meeting decisions and updated remarks

Study of further docs and sources, 06/08 - 07/08/18

The test results, even if not as good as expected, showed that a real-time application with the given constraints might also be able to run with determinism on a virtualized host. In addition, the study of the documentations of the involved technologies and tools brought additional information. During my last investigation on `cgroups` and how they might be used in Docker/Balena, I bumped into a file that mentions, for the first time, an implementation of a Earliest Deadline First (EDF) based scheduling algorithm, [28]. Following the description I found then in another text ([29]) a discussion on a patch release going to be implemented on a mainline kernel version soon. Actually, there exist some recent papers which started to experiment with the EDF scheduler on a PREEMPT-RT patched system [30]. By further investigating on kernel source files on Kernel.org, and reading through sources, I found links to documentation [31] which stated that the completeness of the EDF is only recent.

"Since kernel 4.13, SCHED_DEADLINE completed CBS with the Greedy Reclamation of Unused Bandwidth (GRUB) algorithm. The support has been developed by ReTiS Lab with the collaboration of Evidence Srl."

Indeed, in the repository of the `chrt` standard scheduling tools [32] it can be seen that the version of tools starting from v2.28, version released with Ubuntu 16.04 is v2.27, permit input of parameters for EDF scheduling. Thus, the late completeness of the scheduling option might be one of the reasons for the total lack of documentation.

In addition, the source code gave insight into another work in progress: the scheduling mode SCHED_ISO. It is intended for fast interactive real-time tasks to be run for very short computation times. All in all, this suggests that the standard Linux scheduler development is still ongoing. It would therefore be interesting to exchange information with, if not take part, the main scheduling development team of the Linux kernel.

The study of the AWS system highlighted some recent changes. While the traditional systems are still based on XEN, which uses a CFS CPU scheduler [24], more recent virtual instances like the C5 use a new hypervisor based on KVM [33]. This new hypervisor will allow direct assignment and control of hardware and resources. This means, in short, that there is no need to use bare metal server instead: the new instances promise comparable performance with greater flexibility and scalability.

In the last meeting it was finally decided to continue with Docker as a main containerization platform. Furthermore, Kubernetes will be introduced as management tool for the containers. One of the reasons is that, at the moment, the system of Figure 1 is based on such technology and thus it would reduce the training cost of operators. In sight of findings about the latest hypervisor development on Amazon AWS and the Xenomai recompilation requirements, in the meeting of the 07/08/18 we decided to operate on a C5 instance with at least 4 cores for the containers and, in addition, a generic instance for a Kubernetes monitoring system. All further systems, where possible, will be running on Ubuntu Server 18.04.x with the PREEMPT-RT patch in order to stay updated with the tools and exploit the 5 year maintenance of the LTS program.

7 Concluding steps

Clean system setup & test repeat, 08/08 - 10/08/18

In the last days of the stay, a clean setup with the new Ubuntu Server 18.04.1 LTS has been performed. The latest kernel has been used (4.18-rc) and patched with the PREEMPT-RT patch to verify the updated capabilities. All images, headers and resulting scripts have been uploaded to the repository [11]. In additional test-runs it will be possible to compare the different configurations and choose the best option, including the latest "completed" EDF schedule option.

As a concluding work, a test script (exec.sh) has been created to automate all the test steps performed in Section 5. The script is in the sub-folder `test-monitor` of the project repository [11] and has to be run with root privileges. In addition to the details described in the section, a monitoring program is run to capture the host machine status. The running test command also will run as many testing threads as there are vCPUs available for real-time tasks. The output files are stored in the repository and can be consulted for further studying.

Before the script can be run, a few pre-configuration steps have to be done. The commands are sent via SSH, thus an automatic authentication has to be setup. In addition, the user running the remote commands must have the privileges to create real-time tasks. To keep things simple, in our test setup we will execute everything as root. If you need to test in production, change the script to a different or parameterized authentication.

Steps to be done before the script can be executed:

- on the virtual guest, set a root password, `sudo passwd root`
- on the virtual guest, set `PermitRootLogin` to yes in `/etc/ssh/sshd_config`, and restart the shell daemon via `sudo service ssh restart`
- on the host, generate a ssh key for root. Enter as root in a shell and then type `ssh-keygen`
- copy the key from the host to the guest via `ssh-copy-id root@localhost -p 8022`
- now the parameter PermitRootLogin can also be set back to the defaul value
- install the nmon system monitor via apt-get

Now the script can be run. The parameters to be passed are host, port and virtual host PID. The script will write the results in csv and txt files respectively (See test-monitor folder for further details).

8 Future work

Report clean-up, future work discussions, 11/08 - 28/08/18

For the following weeks more tests could clarify additional behavior of virtual machines in a computation cloud. An example is a test run on dedicated server with four or more cores. A hardware solution containing multiple NUMA nodes would enable to verify improvements through reduced cache misses. The new setup should use a native KVM hypervisor to allow also vCPU thread pinning. The new tests should shed light on the described phenomenon where the last vCPU always gives better results than the others. On the software side, aside from test repetition with the Xenomai image for comparison, some tests still to be performed are performance results using the newest releases. A discussed variant is also to patch the host's kernel for hard-real-time operation. All the tests will be performed with scripts and data recording. The results might then be elaborated for further studying and/or publication. Finally, a dummy application run in a set of containers will allow to study the scheduling behavior once an application runs in a container.

9 Meetings

Table 2: List of meetings during the stay at UC Berkeley

Date	Participants	Topics
25/07/18	Martin Sehr, Ines Ugalde Diaz, Antonio Iannopollo, Edward Kim	Project setup, generic requirements, questions for BU
26/07/18	Martin Sehr, Ines Ugalde Diaz, Antonio Iannopollo, Florian Hofer	Project setup, generic requirements, questions for BU
31/07/18	Martin Sehr, Ines Ugalde Diaz, Florian Hofer	Progress of testing, Dummy testing approach
07/08/18	Martin Sehr, Ines Ugalde Diaz, Antonio Iannopollo, Florian Hofer	Switch to Docker and Kubernetes in Ubuntu Server 18.04
10/08/18	Martin Sehr, Ines Ugalde Diaz, Florian Hofer	"Suspended"

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