Virtualization of a Real-Time Operating System for Robot Control with a Focus on Real-Time Compliance

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Introduction

- Robots perform time-critical tasks
- Real-time = deterministic and predictable
- Delays → catastrophic consequences
- General-Purpose Operating System vs. Real-Time Operating System

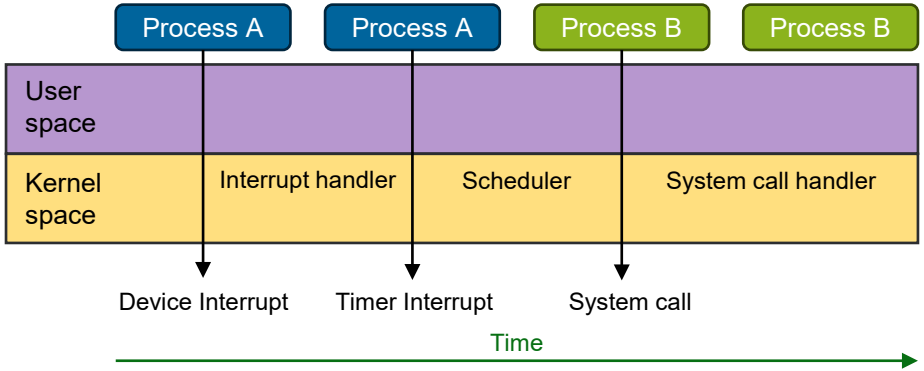


Figure 1: Non-preemptible Kernel [1]

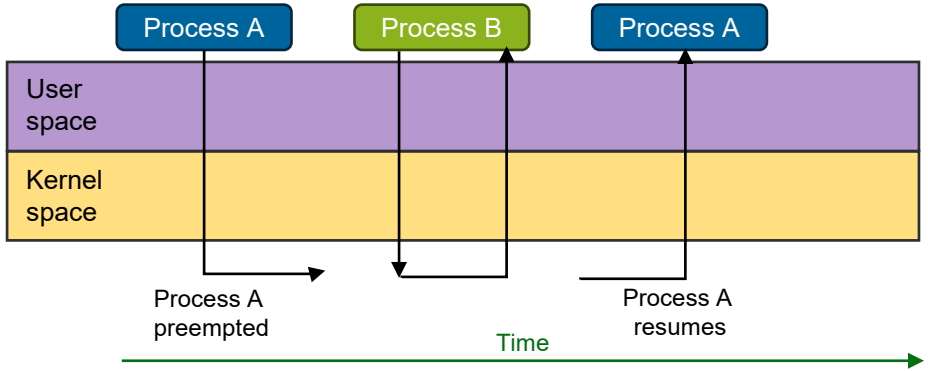


Figure 2: Preemptible Kernel [1]

Problem and Task Definition

Virtualization of Real-Time Operating Systems	
Advantages	**Disadvantages**
Scalability & flexibility	Increased overhead and latency
Cheaper	Performance variability
Remote management	Complexity

- **Research Question:** Is it possible, and if so, how can the latency of a real-time operating system virtualization be reduced using Yocto, Xenomai, and QEMU to a level that is closer to that of bare metal (below 50 µs)?

Application Context and Conditions

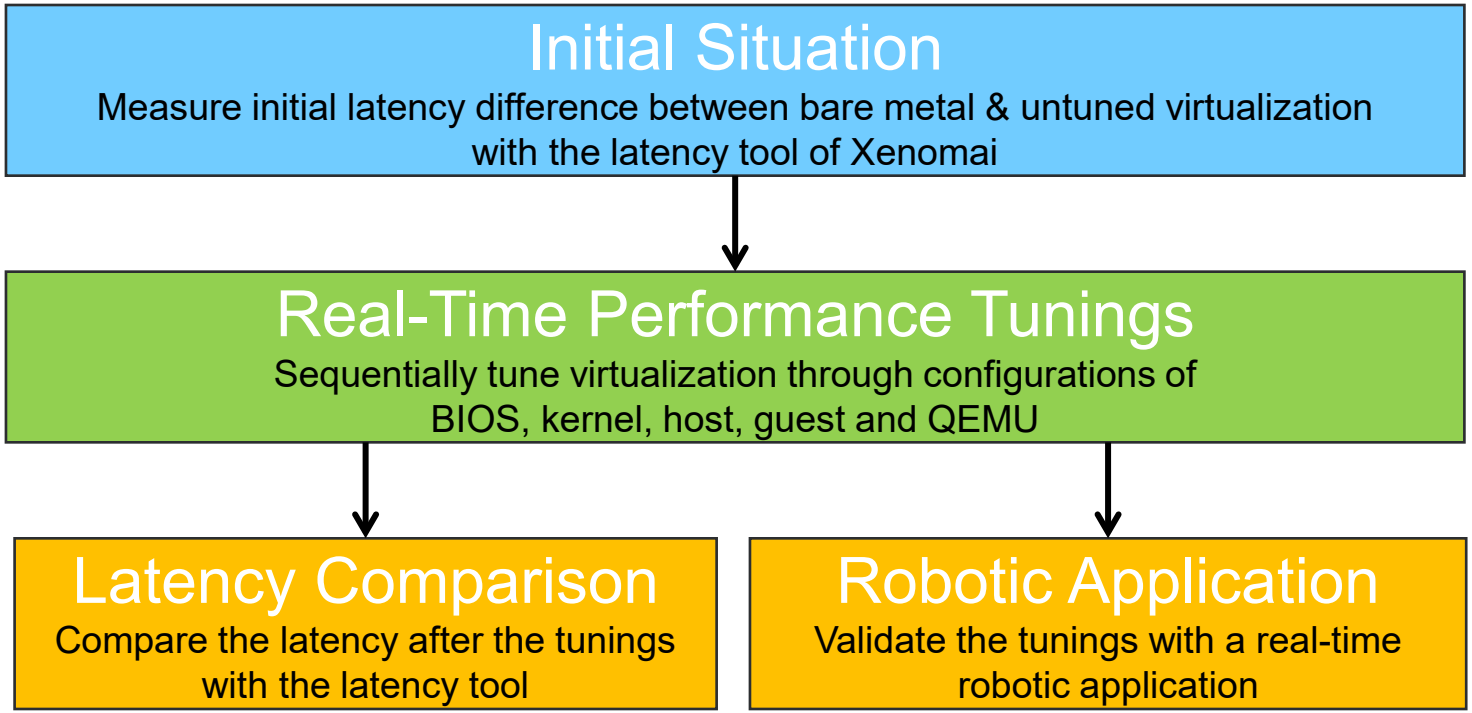
- This work was written at SIGMATEK GmbH & Co KG

- **Host OS:** Ubuntu 22.04.4 LTS, PREEMPT-RT

- **Guest OS:** Salamander 4
  - Built with Yocto [2]
  - Virtualized through Quick Emulator (QEMU) [3]
  - Hard real-time with Xenomai 3 [4]

- Trace-cmd [5] and Kernelshark [6] for kernel tracing and visualization

Methodology



Results – Latency Comparison

- 10 minutes with a sampling period of 100 µs, priority of 99

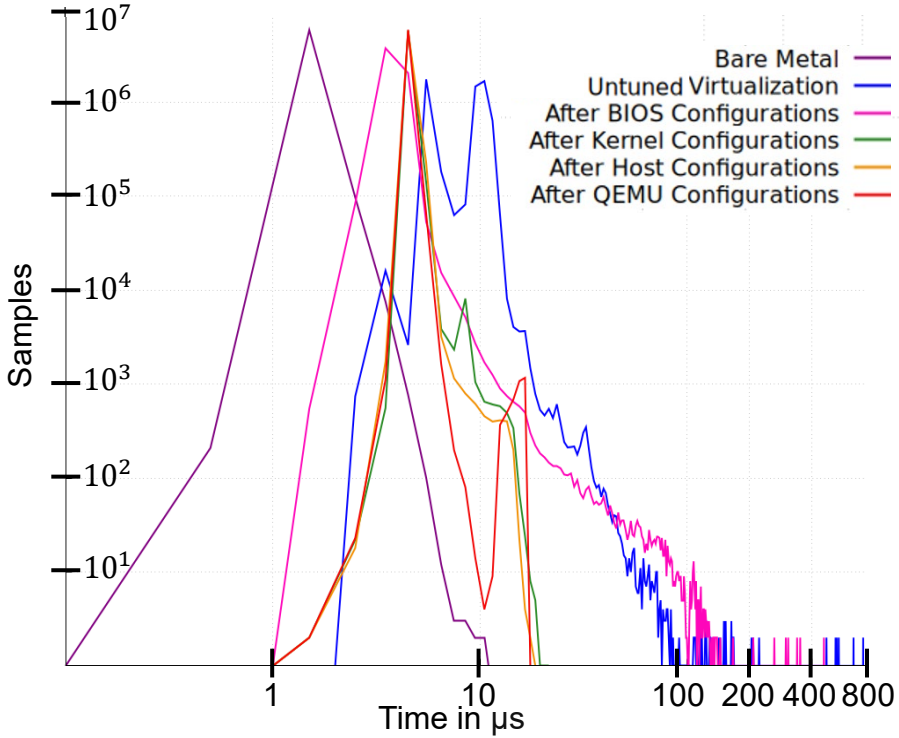


Figure 1: Comparison of Latency Distributions

Version	Latency (µs)			Overruns
	Min	Avg	Max	
Bare Metal	0.613	1.380	10.709	0
Untuned Virtualization	2.536	8.940	707.622	43
After BIOS Configurations	0.969	3.948	457.545	22
After Kernel Configurations	2.545	4.811	21.694	0
After Host Configurations	2.591	4.834	18.441	0
After QEMU Configurations	2.614	4.779	17.134	0

Table 1: Comparison of Latency Results

Results – Robotic Application

- Difference between command issuance time and signal arrival at PWM
- 1,000 samples

Version	Latency (ms)			Std Dev (ms)
	Min	Avg	Max	
Bare Metal	1.211	1.347	1.49	0.082
Untuned Virtualization	3.1	24.603	129.46	13.876
Tuned Virtualization	1.219	2.62	3.988	0.812

Table 2: Comparison of Robotic Application Latency Results

Discussion

✓ Latency Tool

- Worst latency decreased from 707.622 µs to 17.134 µs
- Close to bare metal's 10.709 µs
- No overruns
- Goal achieved

✓ Robotic Application

- Worst latency dropped from 129 ms to 3.988 ms
- Close to bare metal's 1.49 ms
- Tunings validated

Outlook

- Additional configurations
- Other hypervisors and virtualization technologies
- More testing under workloads

References

- [1] https://ubuntu.com/blog/what-is-real-time-linux-ii
- [2] https://docs.yoctoproject.org/
- [3] https://www.qemu.org/
- [4] https://xenomai.org/
- [5] https://trace-cmd.org/
- [6] https://kernelshark.org/

Salamander 4 Bare Metal

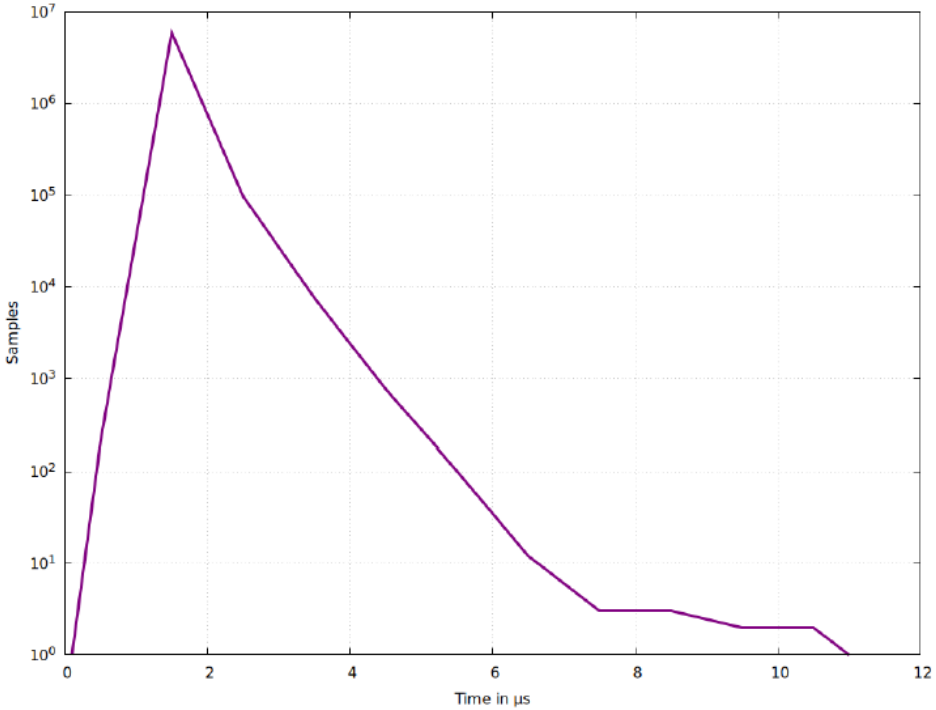


Figure 12: Latency Distribution of Salamander 4 Bare Metal

Table 2: Latency Parameters of Bare Metal

Param	Samples	Average (µs)	Std Dev (µs)
min	599	0.711	0.454
avg	5,999,988	1.019	0.150
max	599	3.528	0.895

Table 3: Minimum, Average, and Maximum Latency with Overrun Counts of Bare Metal

Lat Min (µs)	Lat Avg (µs)	Lat Max (µs)	Overruns
0.613	1.380	10.709	0

Salamander 4 Untuned Virtualization

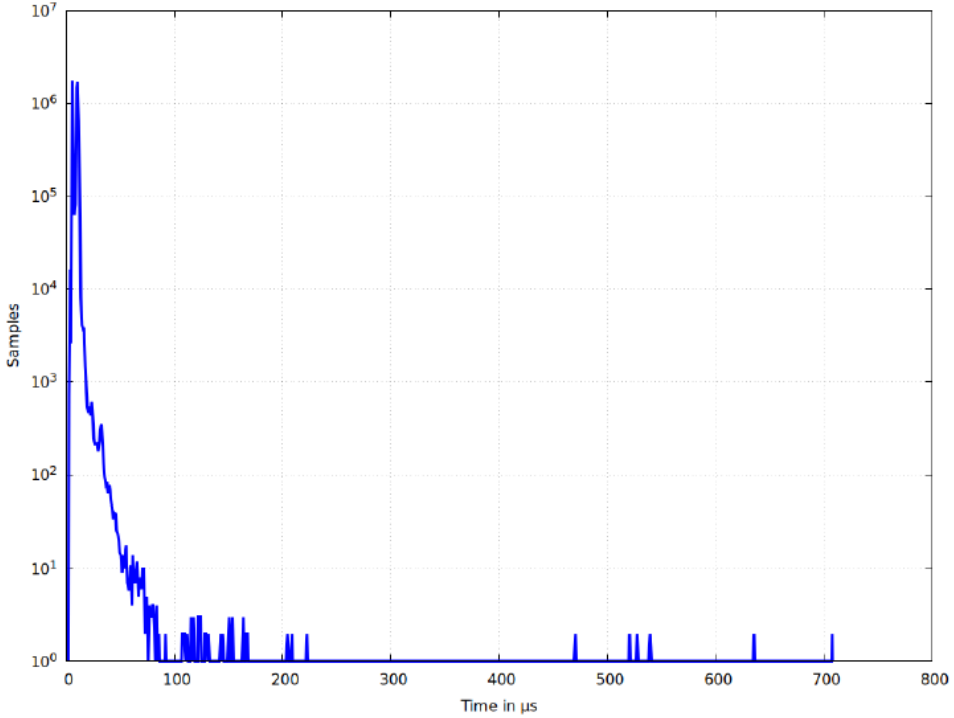


Figure 13: Latency Distribution of Salamander 4 Untuned Virtualization

Table 4: Latency Parameters of Untuned Virtualization

Param	Samples	Average (µs)	Std Dev (µs)
min	599	3.713	1.355
avg	5,999,922	8.247	2.521
max	599	45.705	52.196

Table 5: Minimum, Average, and Maximum Latency with Overrun Counts of Untuned Virtualization

Lat Min (µs)	Lat Avg (µs)	Lat Max (µs)	Overruns
2.536	8.940	707.622	43

Salamander 4 Bare Metal vs. Virtualization

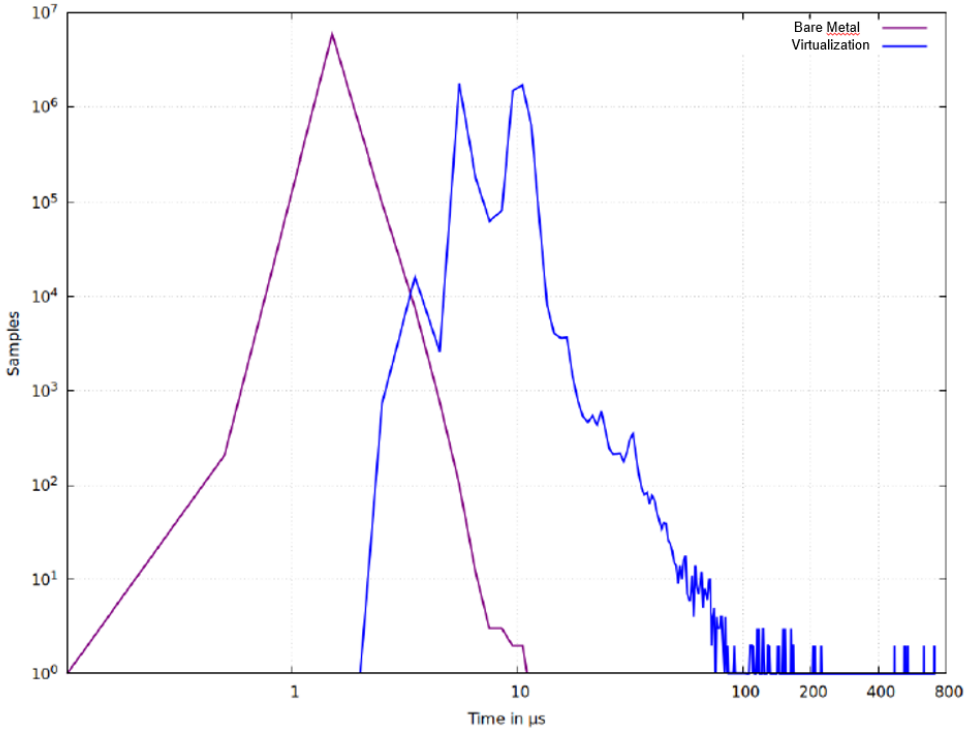


Figure 14: Initial Comparison of Latency Distribution between Bare Metal and Virtualization

Salamander 4 Virtualization BIOS Configurations

Table 6: BIOS Configurations for Real-Time Performance

Option	Status
Hyper Threading	Disabled
Intel SpeedStep®	Disabled
Intel® Speed Shift Technology	Disabled
C-States	Disabled
VT-d	Enabled

Salamander 4 Virtualization after BIOS Configurations

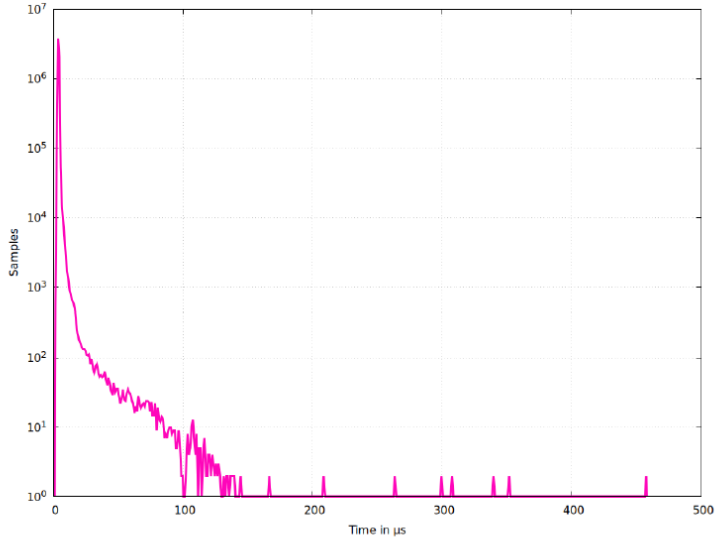


Figure 15: Latency Distribution of Salamander 4 Virtualization after tuning BIOS Configurations

Table 7: Latency Parameters after BIOS Configurations

Param	Samples	Average (µs)	Std Dev (µs)
min	599	1.419	0.507
avg	5,999,885	3.398	1.251
max	599	74.015	26.590

Table 8: Minimum, Average, and Maximum Latency with Overrun Counts after BIOS Configurations

Lat Min (µs)	Lat Avg (µs)	Lat Max (µs)	Overruns
0.969	3.948	457.545	22

Salamander 4 Virtualization Kernel Configurations

```
1       GRUB_CMDLINE_LINUX="isolcpus=4 rcu_nocbs=4 rcu_nocb_poll nohz_full=4
            default_hugepagesz=1G hugepagesz=1G hugepages=8 intel_iommu=on
            rdt=l3cat nmi_watchdog=0 idle=poll clocksource=tsc tsc=reliable audit=0
            skew_tick=1 intel_pstate=disable intel.max_cstate=0
            intel_idle.max_cstate=0 processor.max_cstate=0
            processor_idle.max_cstate=0 nosoftlockup no_timer_check nospectre_v2
            spectre_v2_user=off kvm.kvmclock_periodic_sync=N kvm_intel.ple_gap=0
            irqaffinity=0"
```

Code 5: Kernel Configurations for Real–Time Performance

Salamander 4 Virtualization after Kernel Configurations

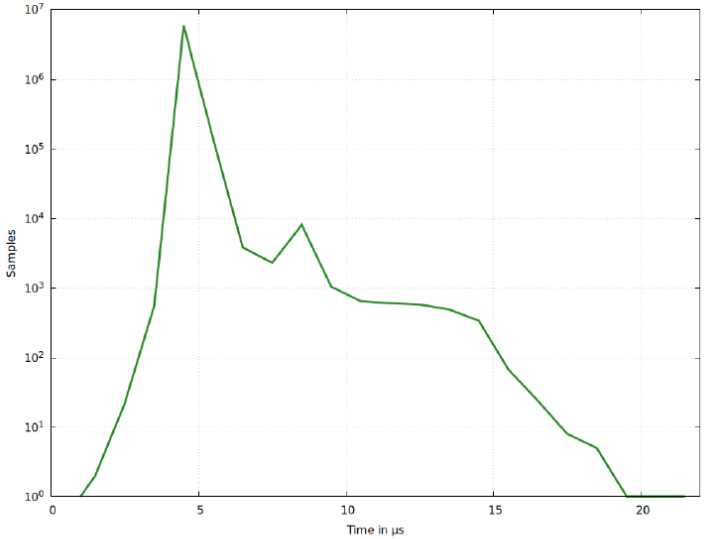


Figure 16: Latency Distribution of Salamander 4 Virtualization after tuning Kernel Configurations

Table 9: Latency Parameters after Kernel Configurations

Param	Samples	Average (µs)	Std Dev (µs)
min	599	3.356	0.551
avg	5,999,972	4.036	0.290
max	599	13.484	1.454

Table 10: Minimum, Average, and Maximum Latency with Overrun Counts after Kernel Configurations

Lat Min (µs)	Lat Avg (µs)	Lat Max (µs)	Overruns
2.545	4.811	21.694	0

Salamander 4 Virtualization Host Configurations

CPU Affinity and Isolation

Interrupt Affinity

RT-Priority

Disable RT Throttling

Disable Timer Migration

Set Device Driver Work Queue

Disable RCU CPU Stall Warnings

Stop Services

Disable Machine Check

Boot into Text-Based Environment

Salamander 4 Virtualization after Host Configurations

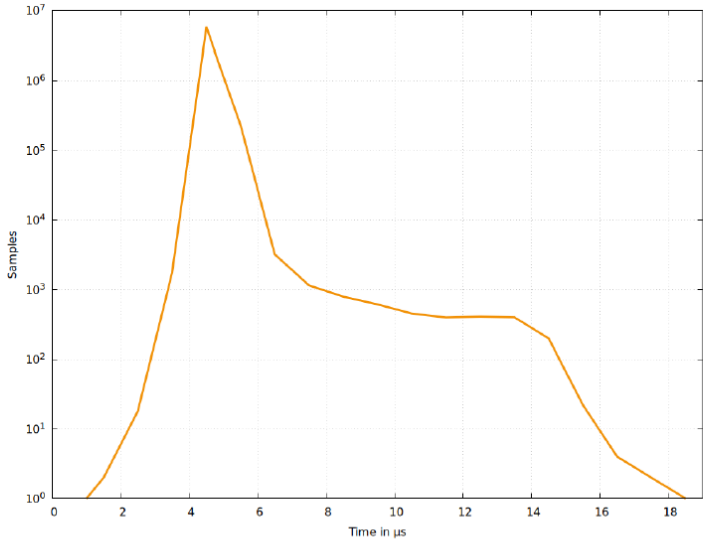


Figure 17: Latency Distribution of Salamander 4 Virtualization after tuning Host Configurations

Table 13: Latency Parameters for Host Configurations

Param	Samples	Average (µs)	Std Dev (µs)
min	599	2.998	0.242
avg	5,999,972	4.043	0.255
max	599	12.124	1.828

Table 14: Minimum, Average, and Maximum Latency with Overrun Counts after Host Configurations

Lat Min (µs)	Lat Avg (µs)	Lat Max (µs)	Overruns
2.591	4.834	18.441	0

Salamander 4 Virtualization QEMU Configurations

```
#!/bin/sh

if  [ ! -d drive-c/ ]; then
      echo "Filling drive-c/"
      mkdir drive-c/
      tar -C drive-c/ -xf stek-drive-c-image-sigmatek-core2.tar.gz
fi

exec taskset -c 4 chrt -f 99 qemu-system-x86_64 -M pc,accel=kvm -kernel
    ./bzImage \
-m 2048 -drive
    file=salamander-image-sigmatek-core2.ext4,format=raw,media=disk \
-append "console=ttyS0 console=tty1 root=/dev/sda rw panic=1
    sigmatek_lrt.QEMU=1 ip=dhcp rootfstype=ext4 schedstats=enable nohlt
    idle=poll quiet xeno_hal.smi=1 xenomai.smi=1 threadirqs" \
-net nic,model=e1000,netdev=e1000 -netdev bridge,id=e1000,br=nm-bridge \
-fsdev local,security_model=none,id=fsdev0,path=drive-c -device
    virtio-9p-pci,id=fs0,fsdev=fsdev0,mount_tag=/mnt/drive-C \
-device vhost-vsock-pci,guest-cid=3,id=vsock0 \
-drive if=pflash,format=qcow2,file=ovmf.code.qcow2 \
-object memory-backend-ram,id=ram0,size=4G,prealloc=on \
-mem-prealloc -mem-path /dev/hugepages \
-device vfio-pci,host=03:00.0 \
-no-reboot -nographic
```

Code 10: Final QEMU Script for Salamander 4 Virtualization with PCI Configuration

Tune LAPIC Timer Advance

Set QEMU Options for Real-Time VM

Priorities for Different Scheduling Policies

Table 11: Minimum and Maximum Priorities for Different Scheduling Policies

Scheduling Policy	Min Priority	Max Priority
SCHED_OTHER	0	0
SCHED_FIFO	1	99
SCHED_RR	1	99
SCHED_BATCH	0	0
SCHED_IDLE	0	0
SCHED_DEADLINE	0	0

Salamander 4 Virtualization after QEMU Configurations

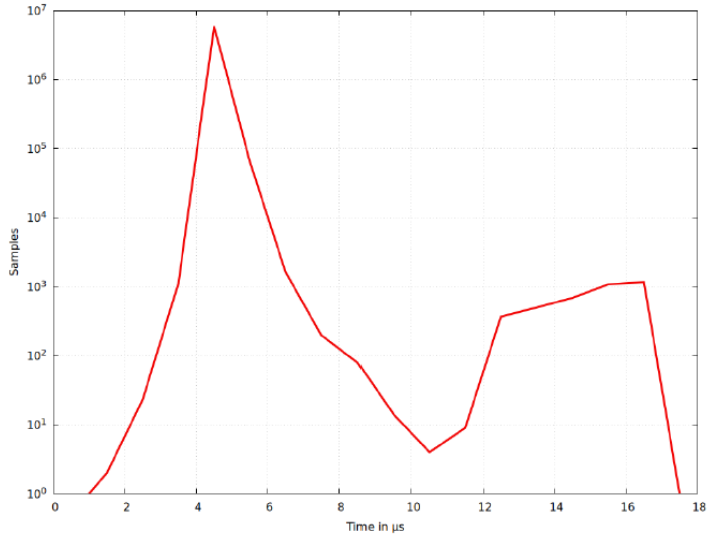


Figure 18: Latency Distribution of Salamander 4 Virtualization after tuning QEMU Configurations

Table 16: Latency Parameters after QEMU Configurations

Param	Samples	Average (µs)	Std Dev (µs)
min	599	3.125	0.432
avg	5,999,973	4.018	0.291
max	599	15.883	0.351

Table 17: Minimum, Average, and Maximum Latency with Overrun Counts after QEMU Configurations

Lat Min (µs)	Lat Avg (µs)	Lat Max (µs)	Overruns
2.614	4.779	17.134	0

Robot

Figure 19: Mini-Robot of the Experiment [60]

Wire Color	Description
Brown	Ground wire connected to the ground of system
Red	Powers the motor typically +5V is used
Orange	PWM signal is given in through this wire to drive the motor

Figure 20: MG996R Servo Motor [62]

Servo Motor with PWM module

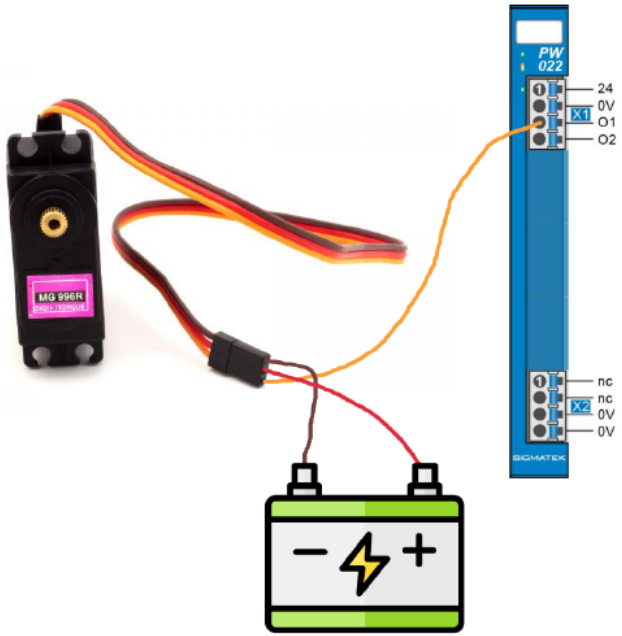


Figure 23: Connection between PW 022 and Mini-Robot [65]

Servo Motor Function

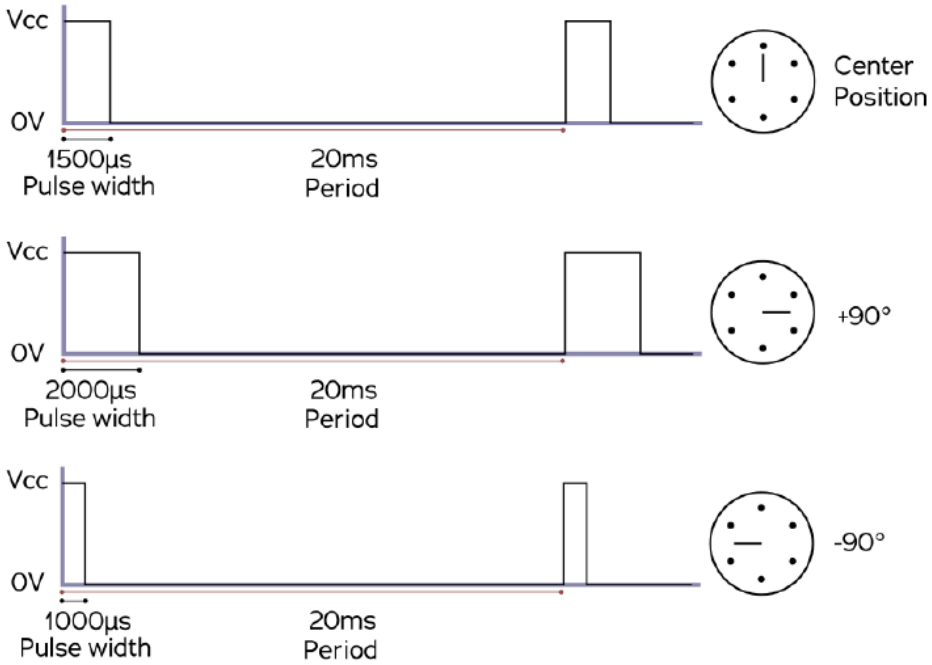


Figure 21: Controlling the MG996R Servo Motor [63]

Robotic Application Setups

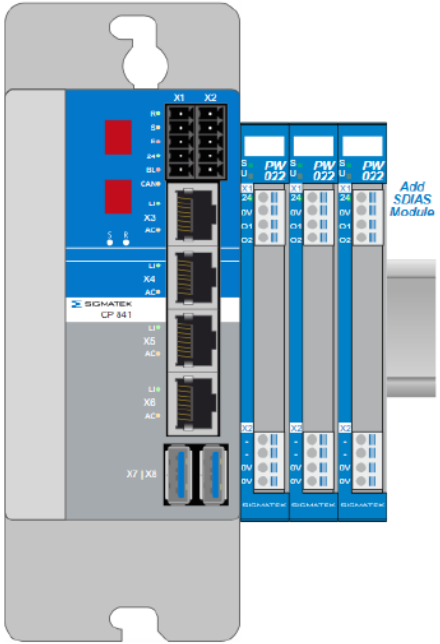


Figure 24: Setup of Salamander 4 Bare Metal

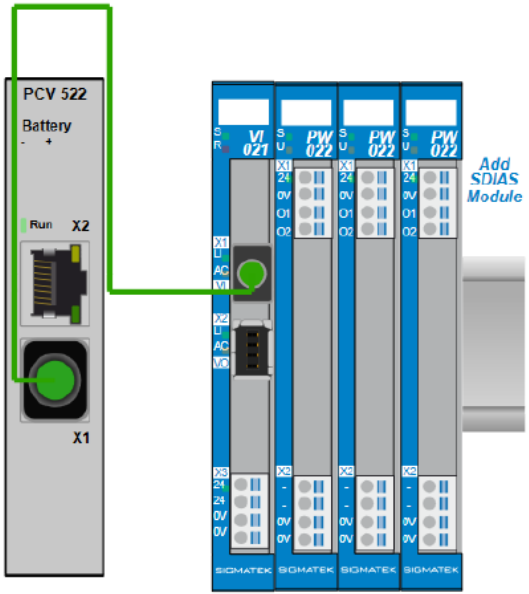


Figure 25: Setup of Salamander 4 Virtualization

Robotic Application Flowchart

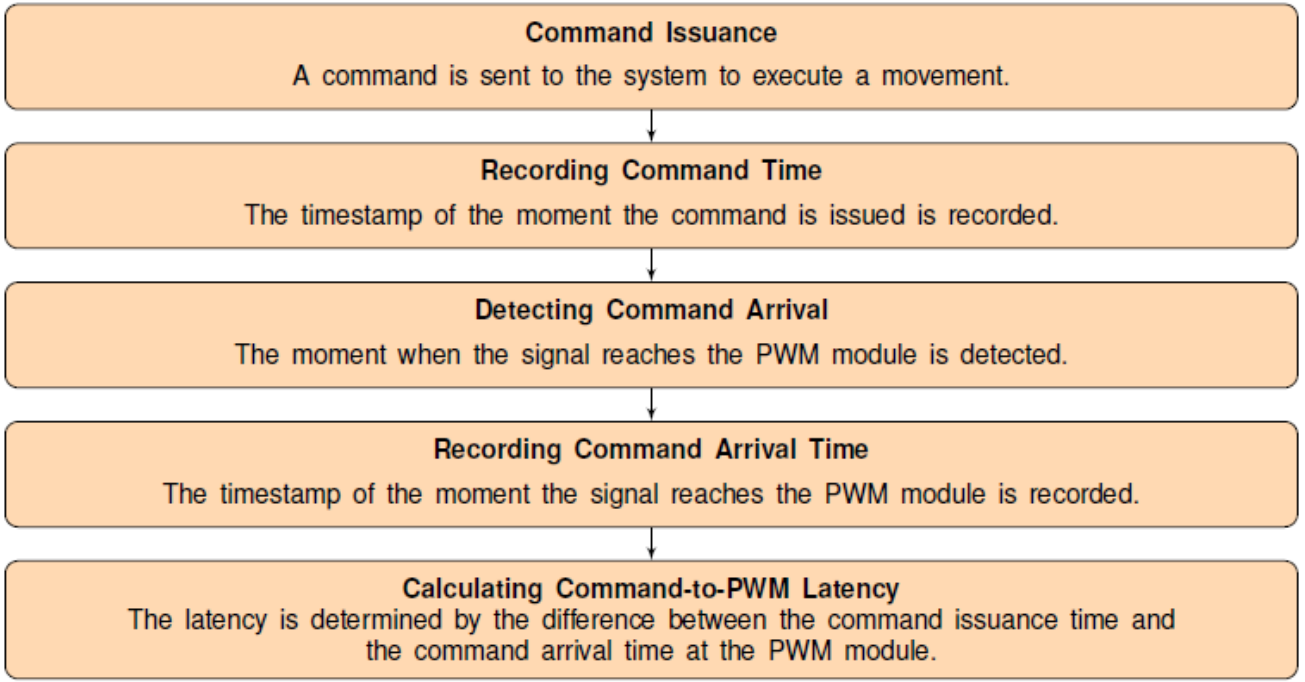


Figure 26: Flowchart of Robotic Application

Results of Robotic Application

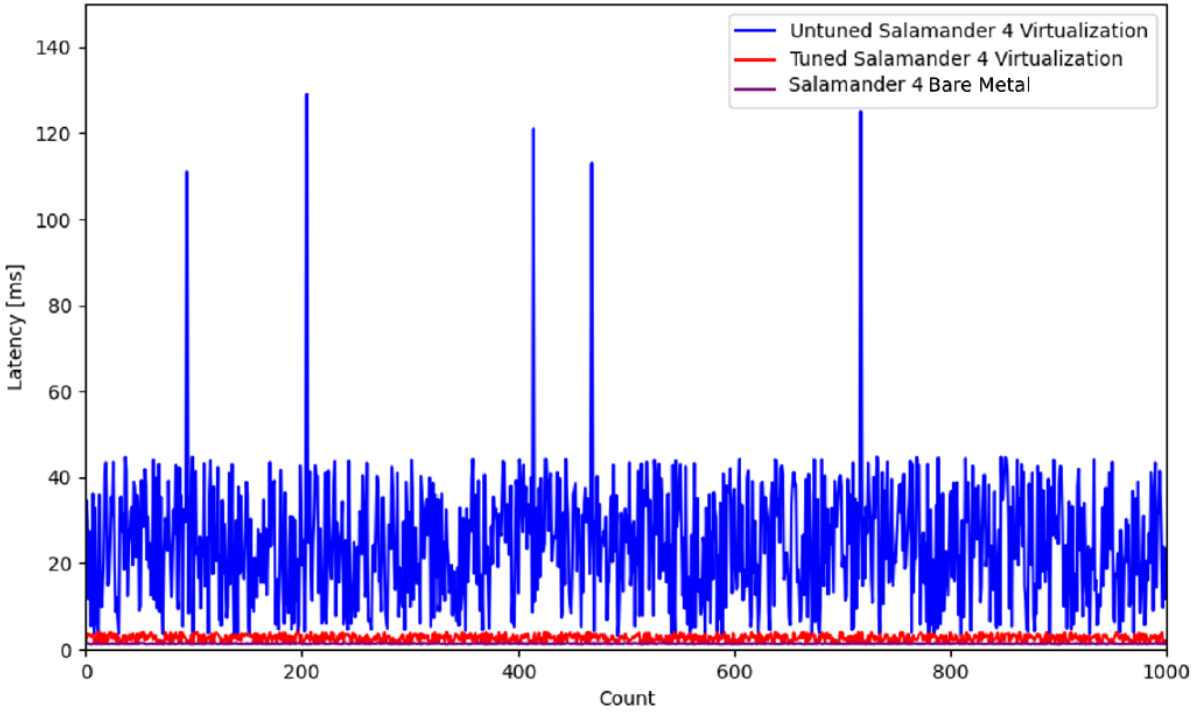


Figure 31: Comparison of Robotic Application Latency after Configurations

Host Operating System

Table 1: Host Operating System Configuration

CPU	Intel(R) Core(TM) i7-8700 CPU @ 3.20GHz, 6 cores
Memory	4 × 8GB DDR4-2666/2400 MHz, 32GB
GPU	Intel UHD Graphics 630 GPU
Storage	500GB NVMe SSD
BIOS	Dell Version 1.29.0
OS	Ubuntu 22.04.4 LTS
Kernel Version	6.8.0-40-generic

Xenomai Approaches

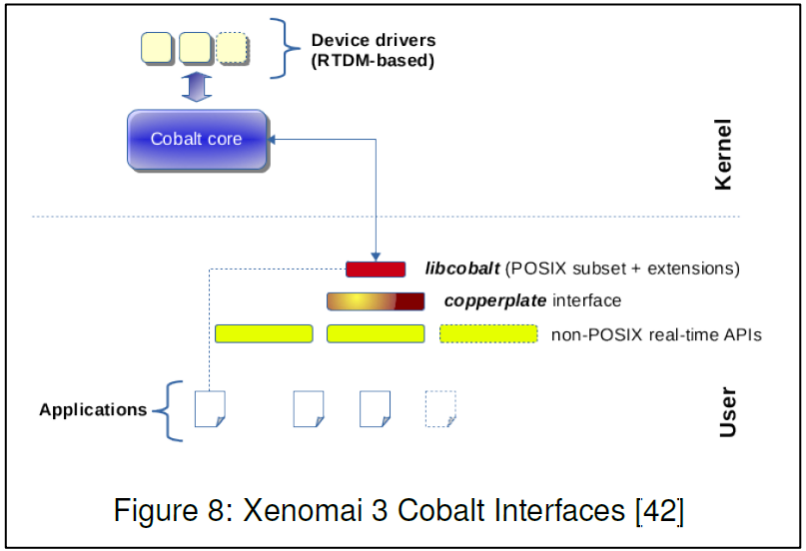


Figure 8: Xenomai 3 Cobalt Interfaces [42]

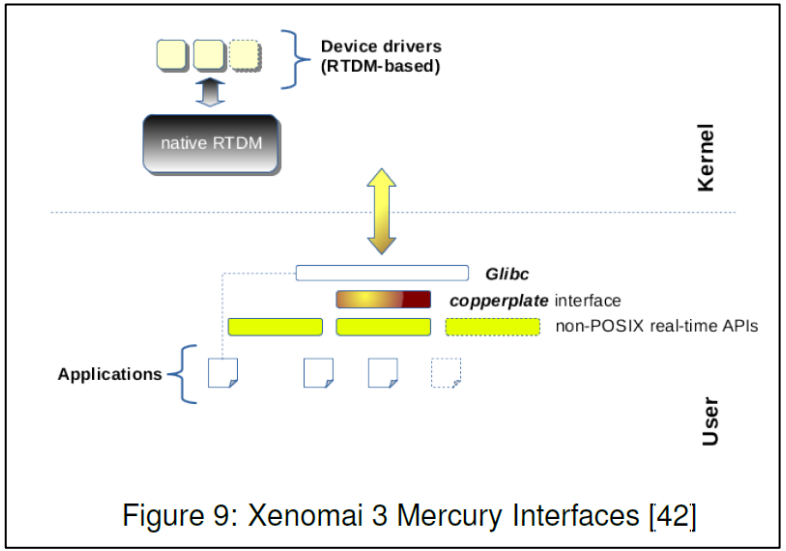


Figure 9: Xenomai 3 Mercury Interfaces [42]

QEMU Script

```
1   #!/bin/sh
2
3   if  [ ! -d drive-c/ ]; then
4         echo "Filling drive-c/"
5         mkdir drive-c/
6         tar -C drive-c/ -xf stek-drive-c-image-sigmatek-core2.tar.gz
7   fi
8
9   exec qemu-system-x86_64 -M pc,accel=kvm -kernel ./bzImage \
10  -m 2048 -drive
        file=salamander-image-sigmatek-core2.ext4,format=raw,media=disk \
11  -append "console=ttyS0 console=tty1 root=/dev/sda rw panic=1
        sigmatek_lrt.QEMU=1 ip=dhcp rootfstype=ext4" \
12  -net nic,model=e1000,netdev=e1000 -netdev bridge,id=e1000,br=nm-bridge \
13  -fsdev local,security_model=none,id=fsdev0,path=drive-c -device
        virtio-9p-pci,id=fs0,fsdev=fsdev0,mount_tag=/mnt/drive-C \
14  -device vhost-vsock-pci,guest-cid=3,id=vsock0 \
15  -drive if=pflash,format=qcow2,file=ovmf.code.qcow2 \
16  -no-reboot -nographic
```

Code 3: QEMU Script for starting Salamander 4 Virtualization

Trace-cmd

```
# Vsockets settings
CONFIG_VSOCKETS=m
CONFIG_VHOST_VSOCK=m
CONFIG_VIRTIO_VSOCKETS=m
CONFIG_VIRTIO_VSOCKETS_COMMON=m
CONFIG_VSOCKETS_DIAG=m
CONFIG_VSOCKETS_LOOPBACK=m
# Tracing settings
CONFIG_TRACING=y
CONFIG_FTRACE=y
CONFIG_FUNCTION_TRACER=y
CONFIG_FUNCTION_GRAPH_TRACER=y
CONFIG_DYNAMIC_FTRACE=y
CONFIG_DYNAMIC_FTRACE_WITH_REGS=y
CONFIG_DYNAMIC_FTRACE_WITH_DIRECT_CALLS=y
CONFIG_DYNAMIC_FTRACE_WITH_ARGS=y
CONFIG_SCHED_TRACER=y
CONFIG_FTRACE_SYSCALLS=y
CONFIG_TRACER_SNAPSHOT=y
CONFIG_KPROBE_EVENTS=y
CONFIG_UPROBE_EVENTS=y
CONFIG_BPF_EVENTS=y
CONFIG_DYNAMIC_EVENTS=y
CONFIG_PROBE_EVENTS=y
CONFIG_SYNTH_EVENTS=y
CONFIG_HIST_TRIGGERS=y
```

Code 4: Kernel Flags for Vsocks and Tracing

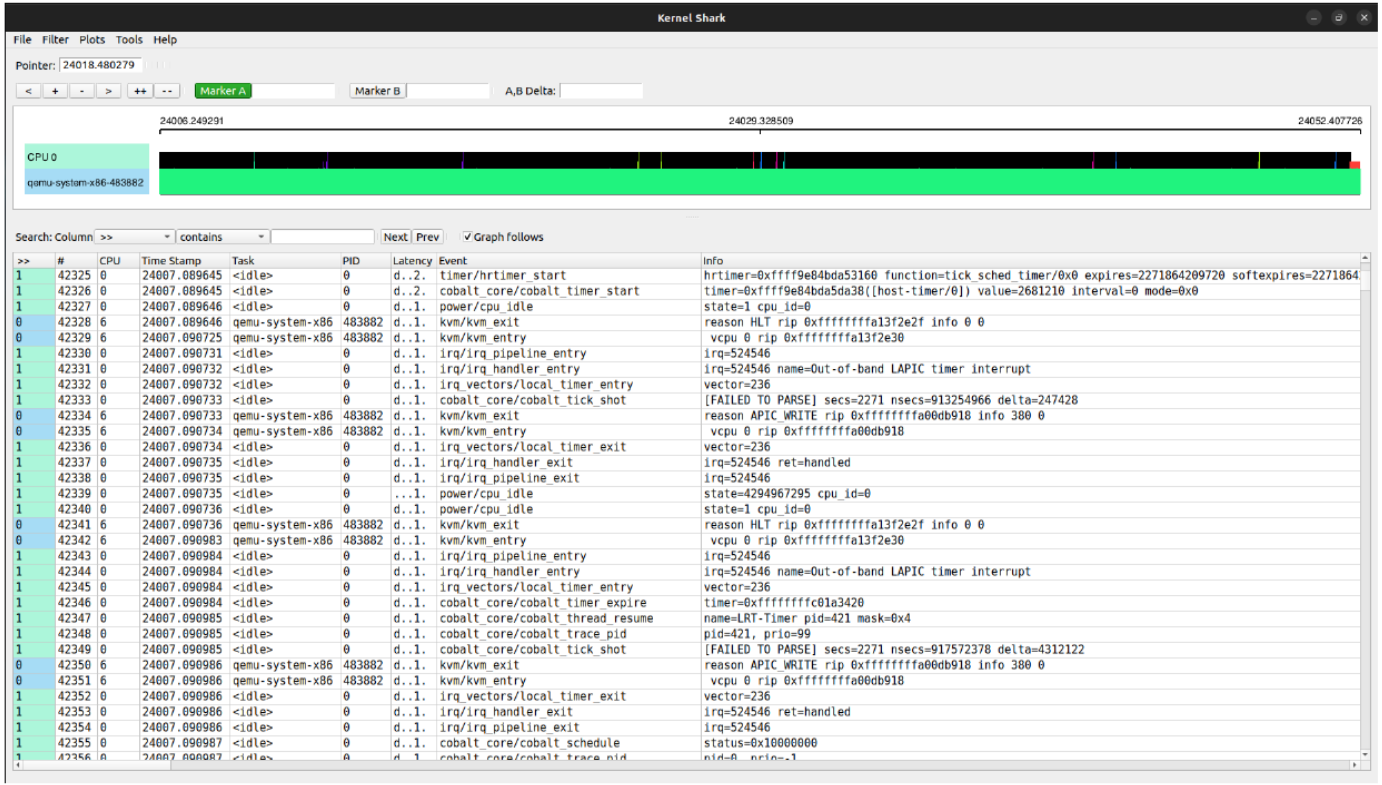
Trace-cmd

- sudo trace-cmd record -e all -A @3:823 -name Salamander4 -e all

- sudo trace-cmd record -e kvm:kvm_entry -e kvm:kvm_exit -A @3:823 -name Salamander4 -e all

- sudo trace-cmd record -e kvm -e sched -e irq -e -A @3:823 -name Salamander4 -e all

Kernelshark



>>	#	CPU	Time Stamp	Task	PID	Latency	Event	Info
1	42325	0	24007.089645	<idle>	0	d..2.	timer/hrtimer_start	hrtimer=0xffff9e84bda53160 function=tick_sched_timer/0x0 expires=2271864209720 softexpires=2271864
1	42326	0	24007.089645	<idle>	0	d..2.	cobalt_core/cobalt_timer_start	timer=0xffff9e84bda5da38([host-timer/0]) value=2681210 interval=0 mode=0x0
1	42327	0	24007.089646	<idle>	0	d..1.	power/cpu_idle	state=1 cpu_id=0
0	42328	6	24007.089646	qemu-system-x86	483882	d..1.	kvm/kvm_exit	reason HLT rip 0xffffffffa13f2e2f info 0 0
0	42329	6	24007.090725	qemu-system-x86	483882	d..1.	kvm/kvm_entry	vcpu 0 rip 0xffffffffa13f2e30
1	42330	0	24007.090731	<idle>	0	d..1.	irq/irq_pipeline_entry	irq=524546
1	42331	0	24007.090732	<idle>	0	d..1.	irq/irq_handler_entry	irq=524546 name=Out-of-band LAPIC timer interrupt
1	42332	0	24007.090732	<idle>	0	d..1.	irq_vectors/local_timer_entry	vector=236
1	42333	0	24007.090733	<idle>	0	d..1.	cobalt_core/cobalt_tick_shot	[FAILED TO PARSE] secs=2271 nsecs=913254966 delta=247428
0	42334	6	24007.090733	qemu-system-x86	483882	d..1.	kvm/kvm_exit	reason APIC_WRITE rip 0xffffffffa00db918 info 380 0
0	42335	6	24007.090734	qemu-system-x86	483882	d..1.	kvm/kvm_entry	vcpu 0 rip 0xffffffffa00db918
1	42336	0	24007.090734	<idle>	0	d..1.	irq_vectors/local_timer_exit	vector=236
1	42337	0	24007.090735	<idle>	0	d..1.	irq/irq_handler_exit	irq=524546 ret=handled
1	42338	0	24007.090735	<idle>	0	d..1.	irq/irq_pipeline_exit	irq=524546
1	42339	0	24007.090735	<idle>	0	...1.	power/cpu_idle	state=4294967295 cpu_id=0
1	42340	0	24007.090736	<idle>	0	d..1.	power/cpu_idle	state=1 cpu_id=0
0	42341	6	24007.090736	qemu-system-x86	483882	d..1.	kvm/kvm_exit	reason HLT rip 0xffffffffa13f2e2f info 0 0
0	42342	6	24007.090983	qemu-system-x86	483882	d..1.	kvm/kvm_entry	vcpu 0 rip 0xffffffffa13f2e30
1	42343	0	24007.090984	<idle>	0	d..1.	irq/irq_pipeline_entry	irq=524546
1	42344	0	24007.090984	<idle>	0	d..1.	irq/irq_handler_entry	irq=524546 name=Out-of-band LAPIC timer interrupt
1	42345	0	24007.090984	<idle>	0	d..1.	irq_vectors/local_timer_entry	vector=236
1	42346	0	24007.090984	<idle>	0	d..1.	cobalt_core/cobalt_timer_expire	timer=0xffffffffc01a3420
1	42347	0	24007.090985	<idle>	0	d..1.	cobalt_core/cobalt_thread_resume	name=LRT-Timer pid=421 mask=0x4
1	42348	0	24007.090985	<idle>	0	d..1.	cobalt_core/cobalt_trace_pid	pid=421, prio=99
1	42349	0	24007.090985	<idle>	0	d..1.	cobalt_core/cobalt_tick_shot	[FAILED TO PARSE] secs=2271 nsecs=917572378 delta=4312122
0	42350	6	24007.090986	qemu-system-x86	483882	d..1.	kvm/kvm_exit	reason APIC_WRITE rip 0xffffffffa00db918 info 380 0
0	42351	6	24007.090986	qemu-system-x86	483882	d..1.	kvm/kvm_entry	vcpu 0 rip 0xffffffffa00db918
1	42352	0	24007.090986	<idle>	0	d..1.	irq_vectors/local_timer_exit	vector=236
1	42353	0	24007.090986	<idle>	0	d..1.	irq/irq_handler_exit	irq=524546 ret=handled
1	42354	0	24007.090986	<idle>	0	d..1.	irq/irq_pipeline_exit	irq=524546
1	42355	0	24007.090987	<idle>	0	d..1.	cobalt_core/cobalt_schedule	status=0x10000000
1	42356	0	24007.090987	<idle>	0	d..1.	cobalt_core/cobalt_trace_pid	pid=0 prio=-1

Figure 10: Guest vCPUs plotted on top of Host Threads in KernelShark