MUSER: mediated userspace device

Thanos Makatos / thanos@nutanix.com
Swapnil Ingle / swapnil.ingle@nutanix.com
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Motivation

• QEMU: de facto device emulation

• Performance/efficiency
  – Multiple virtual devices cannot be emulated by single process
  – Polling virtual drivers prohibitively expensive

• Must use vhost-user
  – Datapath offloading protocol designed around VirtIO
  – Not clean for non-VirtIO devices

• Monolithic emulation
  – Single point of failure
  – Harder to upgrade

• VFIO/mdev \(\rightarrow\) requires kernel vendor driver

• Is there a better way?
MUSER restartable device virtualization (easier upgrade, fault tolerance)

QEMU

VFIO/mdev

device virtualization in kernel space

physical device managed by single context

device virtualization in user space

single context emulates multiple devices

restartable device virtualization
Background

• VFIO (Virtual Function I/O)
  – Allows secure direct device access to user space
  – Physical device can be passed through to VM in QEMU

• VFIO Mediates Devices (mdev)
  – Virtualizes devices that don’t support SR-IOV
  – Partitions of single device passed through to multiple VMs
    ▪ Simultaneously
    ▪ Securely
  – Kernel vendor driver partitions and mediates

• MUSER leverages VFIO/mdev
• Framework for implementing PCI device emulation in user space
  – Implemented as a VFIO mediated device (muser.ko)
  – Forwards ops to user space (libmuser)
  – https://github.com/nutanix/muser

• What does MUSER offer?
  – Single process can emulate multiple devices
  – Complexity hidden (DMA & mem mgmt, IRQs, PCI config space)

• Device emulation app links with libmuser and specifies:
  – Device/vendor ID, PCI regions, #IRQs, PCI caps
  – Callbacks for PCI regions/caps/mmap
MUSER: in a nutshell

• muser.ko
  – Registers with mdev, provides read/write/mmap callbacks
  – Creates char dev for comm. with libmuser
  – Forwards callbacks to libmuser via char dev

• device emulation (libmuser)
  – Opens char dev
  – Sends PCI device configuration
  – Waits for commands and executes user-provided callbacks

• muser.ko/libmuser communication
  – custom ioctl interface
  – libmuser synchronously waits for commands
MUSER internals

DMA, mmap, IRQs
MUSER: DMA map

- Device needs to DMA data from/to guest mem
  - Trivial to do with actual HW
  - QEMU registers guest memory to VFIO

- DMA region registration in MUSER
  - muser.ko injects guest memory into libmuser app context
  - QEMU guest memory must be shared:
    - object memory-backend-file, `share=yes`, ...
  - libmuser provides functions for translating GPA to current VMA
    (pin/unpin in HW terms)
MUSER: mapping device memory

- Optional, useful for high performance
  - Sparse maps supported
- QEMU calls mmap to VFIO fd
- muser.ko notifies libmuser
- libmuser calls back to app, app must use lm_mmap()
- lm_mmap() allocates device memory (mmaps into muser.ko)
  - Requesting libmuser to mmap() simplifies implementation
  - mmap()’ing device done infrequently
- Device memory lives in muser.ko, not freed if libmuser dies
MUSER: interrupts

- QEMU passes IRQ fd to VFIO → muser.ko installs fd into libmuser
- Device emulation can trigger interrupts by calling `lm_irq_trigger()`
- INTx and MSI/X supported
- muser.ko handles gory details
  - `VFIO_DEVICE_SET_IRQS`
  - `VFIO_IRQ_SET_XXX`
typedef struct { /* more stuff ... */
    uint32_t flags;
    uint32_t size;
    lm_region_access_t *fn;
    lm_map_region_t *map; /* optional */
} lm_reg_info_t;

typedef struct {
    irq_count[LM_DEV_NUM_IRQS];
    lm_reg_info_t reg_info[LM_DEV_NUM_REGS];
    lm_pci_hdr_id_t id;
    lm_pci_hdr_ss_t ss;
    lm_pci_hdr_cc_t cc;
} lm_pci_info_t;

typedef struct {
    uint8_t id;
    size_t size;
    lm_cap_access_t *fn;
} lm_cap_t;

typedef struct { /* more stuff ... */
    lm_pci_info_t pci_info;
    int (*reset)(void *pvt); /* optional */
    lm_cap_t caps[LM_MAX_CAPS]; /* optional */
} lm_dev_info_t;

typedef ssize_t (lm_region_access_t)(void *pvt, char *buf, size_t count, loff_t offset, bool is_write);

typedef unsigned long (lm_map_region_t)(void *pvt, unsigned long off, unsigned long len);

typedef ssize_t (lm_cap_access_t)(void *pvt, uint8_t id, char *buf, size_t count, loff_t offset, bool is_write);

lm_ctx_t *lm_ctx_create(lm_dev_info_t *dev_info);
int lm_ctx_drive(lm_ctx_t *ctx);
void lm_ctx_destroy(lm_ctx_t *ctx);
int lm_irq_trigger(lm_ctx_t *ctx, uint32_t subindex);
int lm_addr_to_sg(lm_ctx_t *ctx, dma_addr_t dma_addr, uint32_t len, dma_sg_t *sg, int max_sg);
int lm_map_sg(lm_ctx_t *ctx, int prot, const dma_sg_t *sg, struct iovec *iov, int cnt);
void lm_unmap_sg(lm_ctx_t *ctx, dma_sg_t *sg, struct iovec *iov, int cnt);
MUSER: libmuser API

- app specifies minimum PCI dev characteristics:
  ```c
  lm_dev_info_t dev_info = {
    .pci_info = {
      .id = {.vid = 0x8086, .did = 0x1234},
      .reg_info[LM_BAR0_REG_IDX] = {
        .flags = LM_REG_FLAG_RW,
        .size = 0x40,
        .fn = &bar0,
      },
      .irq_count[LM_DEV_INTX_IRQ_IDX] = 1
    }
  }
  ```

- app specifies dev behavior by providing region callbacks:
  - One callback per region (9 in total, unused left blank)
  - VM accessing a particular region (e.g. reading BAR 0) results in registered callback getting called:
    ```c
    ssize_t bar0(void *pvt, char *buf, size_t count, loff_t offset, bool is_write) {
      // ... return count;
    }
    ```
  - MUSER handles standard PCI header (first 64 bytes)
MUSER: future work

- Live migration
- Restartable libmuser
- Multithreaded libmuser
- Poll for commands from muser.ko
- libmuser can hide even more PCI complexity
- Language bindings (e.g. Python, JavaScript)
- Provide more examples
- Trap mem writes when mmap is used