
Linux Pci Documentation

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The kernel development community

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HOW TO WRITE LINUX PCI DRIVERS

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The world of PCI is vast and full of (mostly unpleasant) surprises. Since each CPU architecture implements different chip-sets and PCI devices have different requirements (erm, "features"), the result is the PCI support in the Linux kernel is not as trivial as one would wish. This short paper tries to introduce all potential driver authors to Linux APIs for PCI device drivers.

A more complete resource is the third edition of "Linux Device Drivers" by Jonathan Corbet, Alessandro Rubini, and Greg Kroah-Hartman. LDD3 is available for free (under Creative Commons License) from: <https://lwn.net/Kernel/LDD3/>.

However, keep in mind that all documents are subject to "bit rot". Refer to the source code if things are not working as described here.

Please send questions/comments/patches about Linux PCI API to the "Linux PCI" <linux-pci@atrey.karlin.mff.cuni.cz> mailing list.

1.1 Structure of PCI drivers

PCI drivers "discover" PCI devices in a system via `pci_register_driver()`. Actually, it's the other way around. When the PCI generic code discovers a new device, the driver with a matching "description" will be notified. Details on this below.

`pci_register_driver()` leaves most of the probing for devices to the PCI layer and supports online insertion/removal of devices [thus supporting hot-pluggable PCI, CardBus, and Express-Card in a single driver]. `pci_register_driver()` call requires passing in a table of function pointers and thus dictates the high level structure of a driver.

Once the driver knows about a PCI device and takes ownership, the driver generally needs to perform the following initialization:

- Enable the device
- Request MMIO/IOP resources
- Set the DMA mask size (for both coherent and streaming DMA)
- Allocate and initialize shared control data (`pci_allocate_coherent()`)
- Access device configuration space (if needed)

- Register IRQ handler (`request_irq()`)
- Initialize non-PCI (i.e. LAN/SCSI/etc parts of the chip)
- Enable DMA/processing engines

When done using the device, and perhaps the module needs to be unloaded, the driver needs to take the follow steps:

- Disable the device from generating IRQs
- Release the IRQ (`free_irq()`)
- Stop all DMA activity
- Release DMA buffers (both streaming and coherent)
- Unregister from other subsystems (e.g. scsi or netdev)
- Release MMIO/IOP resources
- Disable the device

Most of these topics are covered in the following sections. For the rest look at LDD3 or `<linux/pci.h>`.

If the PCI subsystem is not configured (`CONFIG_PCI` is not set), most of the PCI functions described below are defined as inline functions either completely empty or just returning an appropriate error codes to avoid lots of ifdefs in the drivers.

1.2 `pci_register_driver()` call

PCI device drivers call `pci_register_driver()` during their initialization with a pointer to a structure describing the driver (`struct pci_driver`):

```
struct pci_driver  
    PCI driver structure
```

Definition:

```
struct pci_driver {  
    const char                  *name;  
    const struct pci_device_id *id_table;  
    int (*probe)(struct pci_dev *dev, const struct pci_device_id *id);  
    void (*remove)(struct pci_dev *dev);  
    int (*suspend)(struct pci_dev *dev, pm_message_t state);  
    int (*resume)(struct pci_dev *dev);  
    void (*shutdown)(struct pci_dev *dev);  
    int (*sriov_configure)(struct pci_dev *dev, int num_vfs);  
    int (*sriov_set_msix_vec_count)(struct pci_dev *vf, int msix_vec_count);  
    u32 (*sriov_get_vf_total_msix)(struct pci_dev *pf);  
    const struct pci_error_handlers *err_handler;  
    const struct attribute_group **groups;  
    const struct attribute_group **dev_groups;  
    struct device_driver      driver;  
    struct pci_dynids        dynids;
```

```
    bool driver_managed_dma;
};
```

Members**name**

Driver name.

id_table

Pointer to table of device IDs the driver is interested in. Most drivers should export this table using MODULE_DEVICE_TABLE(pci,...).

probe

This probing function gets called (during execution of pci_register_driver() for already existing devices or later if a new device gets inserted) for all PCI devices which match the ID table and are not "owned" by the other drivers yet. This function gets passed a "struct pci_dev **" for each device whose entry in the ID table matches the device. The probe function returns zero when the driver chooses to take "ownership" of the device or an error code (negative number) otherwise. The probe function always gets called from process context, so it can sleep.

remove

The remove() function gets called whenever a device being handled by this driver is removed (either during deregistration of the driver or when it's manually pulled out of a hot-pluggable slot). The remove function always gets called from process context, so it can sleep.

suspend

Put device into low power state.

resume

Wake device from low power state. (Please see Documentation/power/pci.rst for descriptions of PCI Power Management and the related functions.)

shutdown

Hook into reboot_notifier_list (kernel/sys.c). Intended to stop any idling DMA operations. Useful for enabling wake-on-lan (NIC) or changing the power state of a device before reboot. e.g. drivers/net/e100.c.

sriov_configure

Optional driver callback to allow configuration of number of VFs to enable via sysfs "sriov_numvfs" file.

sriov_set_msix_vec_count

PF Driver callback to change number of MSI-X vectors on a VF. Triggered via sysfs "sriov_vf_msix_count". This will change MSI-X Table Size in the VF Message Control registers.

sriov_get_vf_total_msix

PF driver callback to get the total number of MSI-X vectors available for distribution to the VFs.

err_handler

See *PCI Error Recovery*

groups

Sysfs attribute groups.

dev_groups

Attributes attached to the device that will be created once it is bound to the driver.

driver

Driver model structure.

dynids

List of dynamically added device IDs.

driver_managed_dma

Device driver doesn't use kernel DMA API for DMA. For most device drivers, no need to care about this flag as long as all DMAs are handled through the kernel DMA API. For some special ones, for example VFIO drivers, they know how to manage the DMA themselves and set this flag so that the IOMMU layer will allow them to setup and manage their own I/O address space.

The ID table is an array of `struct pci_device_id` entries ending with an all-zero entry. Definitions with static const are generally preferred.

struct pci_device_id

PCI device ID structure

Definition:

```
struct pci_device_id {  
    __u32 vendor, device;  
    __u32 subvendor, subdevice;  
    __u32 class, class_mask;  
    kernel_ulong_t driver_data;  
    __u32 override_only;  
};
```

Members

vendor

Vendor ID to match (or PCI_ANY_ID)

device

Device ID to match (or PCI_ANY_ID)

subvendor

Subsystem vendor ID to match (or PCI_ANY_ID)

subdevice

Subsystem device ID to match (or PCI_ANY_ID)

class

Device class, subclass, and "interface" to match. See Appendix D of the PCI Local Bus Spec or include/linux/pci_ids.h for a full list of classes. Most drivers do not need to specify class/class_mask as vendor/device is normally sufficient.

class_mask

Limit which sub-fields of the class field are compared. See drivers/scsi/sym53c8xx_2/ for example of usage.

driver_data

Data private to the driver. Most drivers don't need to use driver_data field. Best practice is

to use driver_data as an index into a static list of equivalent device types, instead of using it as a pointer.

override_only

Match only when dev->driver_override is this driver.

Most drivers only need PCI_DEVICE() or PCI_DEVICE_CLASS() to set up a pci_device_id table.

New PCI IDs may be added to a device driver pci_ids table at runtime as shown below:

```
echo "vendor device subvendor subdevice class class_mask driver_data" > \
/sys/bus/pci/drivers/{driver}/new_id
```

All fields are passed in as hexadecimal values (no leading 0x). The vendor and device fields are mandatory, the others are optional. Users need pass only as many optional fields as necessary:

- subvendor and subdevice fields default to PCI_ANY_ID (FFFFFFFF)
- class and classmask fields default to 0
- driver_data defaults to 0UL.
- override_only field defaults to 0.

Note that driver_data must match the value used by any of the pci_device_id entries defined in the driver. This makes the driver_data field mandatory if all the pci_device_id entries have a non-zero driver_data value.

Once added, the driver probe routine will be invoked for any unclaimed PCI devices listed in its (newly updated) pci_ids list.

When the driver exits, it just calls pci_unregister_driver() and the PCI layer automatically calls the remove hook for all devices handled by the driver.

1.2.1 "Attributes" for driver functions/data

Please mark the initialization and cleanup functions where appropriate (the corresponding macros are defined in <linux/init.h>):

<u>_init</u>	Initialization code. Thrown away after the driver initializes.
<u>_exit</u>	Exit code. Ignored for non-modular drivers.

Tips on when/where to use the above attributes:

- The module_init()/module_exit() functions (and all initialization functions called _only_ from these) should be marked __init/__exit.
- Do not mark the *struct pci_driver*.
- Do NOT mark a function if you are not sure which mark to use. Better to not mark the function than mark the function wrong.

1.3 How to find PCI devices manually

PCI drivers should have a really good reason for not using the `pci_register_driver()` interface to search for PCI devices. The main reason PCI devices are controlled by multiple drivers is because one PCI device implements several different HW services. E.g. combined serial/parallel port/floppy controller.

A manual search may be performed using the following constructs:

Searching by vendor and device ID:

```
struct pci_dev *dev = NULL;
while (dev = pci_get_device(VENDOR_ID, DEVICE_ID, dev))
    configure_device(dev);
```

Searching by class ID (iterate in a similar way):

```
pci_get_class(CLASS_ID, dev)
```

Searching by both vendor/device and subsystem vendor/device ID:

```
pci_get_subsys(VENDOR_ID,DEVICE_ID, SUBSYS_VENDOR_ID, SUBSYS_DEVICE_ID, dev).
```

You can use the constant `PCI_ANY_ID` as a wildcard replacement for `VENDOR_ID` or `DEVICE_ID`. This allows searching for any device from a specific vendor, for example.

These functions are hotplug-safe. They increment the reference count on the `pci_dev` that they return. You must eventually (possibly at module unload) decrement the reference count on these devices by calling `pci_dev_put()`.

1.4 Device Initialization Steps

As noted in the introduction, most PCI drivers need the following steps for device initialization:

- Enable the device
- Request MMIO/IOP resources
- Set the DMA mask size (for both coherent and streaming DMA)
- Allocate and initialize shared control data (`pci_allocate_coherent()`)
- Access device configuration space (if needed)
- Register IRQ handler (`request_irq()`)
- Initialize non-PCI (i.e. LAN/SCSI/etc parts of the chip)
- Enable DMA/processing engines.

The driver can access PCI config space registers at any time. (Well, almost. When running BIST, config space can go away...but that will just result in a PCI Bus Master Abort and config reads will return garbage).

1.4.1 Enable the PCI device

Before touching any device registers, the driver needs to enable the PCI device by calling `pci_enable_device()`. This will:

- wake up the device if it was in suspended state,
- allocate I/O and memory regions of the device (if BIOS did not),
- allocate an IRQ (if BIOS did not).

Note: `pci_enable_device()` can fail! Check the return value.

Warning: OS BUG: we don't check resource allocations before enabling those resources. The sequence would make more sense if we called `pci_request_resources()` before calling `pci_enable_device()`. Currently, the device drivers can't detect the bug when two devices have been allocated the same range. This is not a common problem and unlikely to get fixed soon.

This has been discussed before but not changed as of 2.6.19: <https://lore.kernel.org/r/20060302180025.GC28895@flint.arm.linux.org.uk/>

`pci_set_master()` will enable DMA by setting the bus master bit in the PCI_COMMAND register. It also fixes the latency timer value if it's set to something bogus by the BIOS. `pci_clear_master()` will disable DMA by clearing the bus master bit.

If the PCI device can use the PCI Memory-Write-Invalidate transaction, call `pci_set_mwi()`. This enables the PCI_COMMAND bit for Mem-Wr-Inval and also ensures that the cache line size register is set correctly. Check the return value of `pci_set_mwi()` as not all architectures or chip-sets may support Memory-Write-Invalidate. Alternatively, if Mem-Wr-Inval would be nice to have but is not required, call `pci_try_set_mwi()` to have the system do its best effort at enabling Mem-Wr-Inval.

1.4.2 Request MMIO/IOP resources

Memory (MMIO), and I/O port addresses should NOT be read directly from the PCI device config space. Use the values in the `pci_dev` structure as the PCI "bus address" might have been remapped to a "host physical" address by the arch/chip-set specific kernel support.

See Documentation/driver-api/io-mapping.rst for how to access device registers or device memory.

The device driver needs to call `pci_request_region()` to verify no other device is already using the same address resource. Conversely, drivers should call `pci_release_region()` AFTER calling `pci_disable_device()`. The idea is to prevent two devices colliding on the same address range.

Tip: See OS BUG comment above. Currently (2.6.19), The driver can only determine MMIO and IO Port resource availability _after_ calling `pci_enable_device()`.

Generic flavors of `pci_request_region()` are `request_mem_region()` (for MMIO ranges) and `request_region()` (for IO Port ranges). Use these for address resources that are not described by "normal" PCI BARs.

Also see `pci_request_selected_regions()` below.

1.4.3 Set the DMA mask size

Note: If anything below doesn't make sense, please refer to Documentation/core-api/dma-api.rst. This section is just a reminder that drivers need to indicate DMA capabilities of the device and is not an authoritative source for DMA interfaces.

While all drivers should explicitly indicate the DMA capability (e.g. 32 or 64 bit) of the PCI bus master, devices with more than 32-bit bus master capability for streaming data need the driver to "register" this capability by calling `dma_set_mask()` with appropriate parameters. In general this allows more efficient DMA on systems where System RAM exists above 4G _physical_address.

Drivers for all PCI-X and PCIe compliant devices must call `dma_set_mask()` as they are 64-bit DMA devices.

Similarly, drivers must also "register" this capability if the device can directly address "coherent memory" in System RAM above 4G physical address by calling `dma_set_coherent_mask()`. Again, this includes drivers for all PCI-X and PCIe compliant devices. Many 64-bit "PCI" devices (before PCI-X) and some PCI-X devices are 64-bit DMA capable for payload ("streaming") data but not control ("coherent") data.

1.4.4 Setup shared control data

Once the DMA masks are set, the driver can allocate "coherent" (a.k.a. shared) memory. See Documentation/core-api/dma-api.rst for a full description of the DMA APIs. This section is just a reminder that it needs to be done before enabling DMA on the device.

1.4.5 Initialize device registers

Some drivers will need specific "capability" fields programmed or other "vendor specific" register initialized or reset. E.g. clearing pending interrupts.

1.4.6 Register IRQ handler

While calling `request_irq()` is the last step described here, this is often just another intermediate step to initialize a device. This step can often be deferred until the device is opened for use.

All interrupt handlers for IRQ lines should be registered with `IRQF_SHARED` and use the `devid` to map IRQs to devices (remember that all PCI IRQ lines can be shared).

`request_irq()` will associate an interrupt handler and device handle with an interrupt number. Historically interrupt numbers represent IRQ lines which run from the PCI device to the Interrupt controller. With MSI and MSI-X (more below) the interrupt number is a CPU "vector".

`request_irq()` also enables the interrupt. Make sure the device is quiesced and does not have any interrupts pending before registering the interrupt handler.

MSI and MSI-X are PCI capabilities. Both are "Message Signaled Interrupts" which deliver interrupts to the CPU via a DMA write to a Local APIC. The fundamental difference between MSI and MSI-X is how multiple "vectors" get allocated. MSI requires contiguous blocks of vectors while MSI-X can allocate several individual ones.

MSI capability can be enabled by calling `pci_alloc_irq_vectors()` with the `PCI_IRQ_MSI` and/or `PCI_IRQ_MSIX` flags before calling `request_irq()`. This causes the PCI support to program CPU vector data into the PCI device capability registers. Many architectures, chipsets, or BIOSes do NOT support MSI or MSI-X and a call to `pci_alloc_irq_vectors` with just the `PCI_IRQ_MSI` and `PCI_IRQ_MSIX` flags will fail, so try to always specify `PCI_IRQ_LEGACY` as well.

Drivers that have different interrupt handlers for MSI/MSI-X and legacy INTx should chose the right one based on the `msi_enabled` and `msix_enabled` flags in the `pci_dev` structure after calling `pci_alloc_irq_vectors`.

There are (at least) two really good reasons for using MSI:

- 1) MSI is an exclusive interrupt vector by definition. This means the interrupt handler doesn't have to verify its device caused the interrupt.
- 2) MSI avoids DMA/IRQ race conditions. DMA to host memory is guaranteed to be visible to the host CPU(s) when the MSI is delivered. This is important for both data coherency and avoiding stale control data. This guarantee allows the driver to omit MMIO reads to flush the DMA stream.

See drivers/infiniband/hw/mthca/ or drivers/net/tg3.c for examples of MSI/MSI-X usage.

1.5 PCI device shutdown

When a PCI device driver is being unloaded, most of the following steps need to be performed:

- Disable the device from generating IRQs
- Release the IRQ (`free_irq()`)
- Stop all DMA activity
- Release DMA buffers (both streaming and coherent)
- Unregister from other subsystems (e.g. scsi or netdev)
- Disable device from responding to MMIO/IO Port addresses
- Release MMIO/IO Port resource(s)

1.5.1 Stop IRQs on the device

How to do this is chip/device specific. If it's not done, it opens the possibility of a "screaming interrupt" if (and only if) the IRQ is shared with another device.

When the shared IRQ handler is "unhooked", the remaining devices using the same IRQ line will still need the IRQ enabled. Thus if the "unhooked" device asserts IRQ line, the system will respond assuming it was one of the remaining devices asserted the IRQ line. Since none of the other devices will handle the IRQ, the system will "hang" until it decides the IRQ isn't going to get handled and masks the IRQ (100,000 iterations later). Once the shared IRQ is masked, the remaining devices will stop functioning properly. Not a nice situation.

This is another reason to use MSI or MSI-X if it's available. MSI and MSI-X are defined to be exclusive interrupts and thus are not susceptible to the "screaming interrupt" problem.

1.5.2 Release the IRQ

Once the device is quiesced (no more IRQs), one can call `free_irq()`. This function will return control once any pending IRQs are handled, "unhook" the drivers IRQ handler from that IRQ, and finally release the IRQ if no one else is using it.

1.5.3 Stop all DMA activity

It's extremely important to stop all DMA operations BEFORE attempting to deallocate DMA control data. Failure to do so can result in memory corruption, hangs, and on some chip-sets a hard crash.

Stopping DMA after stopping the IRQs can avoid races where the IRQ handler might restart DMA engines.

While this step sounds obvious and trivial, several "mature" drivers didn't get this step right in the past.

1.5.4 Release DMA buffers

Once DMA is stopped, clean up streaming DMA first. I.e. unmap data buffers and return buffers to "upstream" owners if there is one.

Then clean up "coherent" buffers which contain the control data.

See Documentation/core-api/dma-api.rst for details on unmapping interfaces.

1.5.5 Unregister from other subsystems

Most low level PCI device drivers support some other subsystem like USB, ALSA, SCSI, NetDev, Infiniband, etc. Make sure your driver isn't losing resources from that other subsystem. If this happens, typically the symptom is an Oops (panic) when the subsystem attempts to call into a driver that has been unloaded.

1.5.6 Disable Device from responding to MMIO/IO Port addresses

`io_unmap()` MMIO or IO Port resources and then call `pci_disable_device()`. This is the symmetric opposite of `pci_enable_device()`. Do not access device registers after calling `pci_disable_device()`.

1.5.7 Release MMIO/IO Port Resource(s)

Call `pci_release_region()` to mark the MMIO or IO Port range as available. Failure to do so usually results in the inability to reload the driver.

1.6 How to access PCI config space

You can use `pci_(read|write)_config_(byte|word|dword)` to access the config space of a device represented by `struct pci_dev *`. All these functions return 0 when successful or an error code (`PCIBIOS_...`) which can be translated to a text string by `pcibios_strerror`. Most drivers expect that accesses to valid PCI devices don't fail.

If you don't have a `struct pci_dev` available, you can call `pci_bus_(read|write)_config_(byte|word|dword)` to access a given device and function on that bus.

If you access fields in the standard portion of the config header, please use symbolic names of locations and bits declared in `<linux/pci.h>`.

If you need to access Extended PCI Capability registers, just call `pci_find_capability()` for the particular capability and it will find the corresponding register block for you.

1.7 Other interesting functions

<code>pci_get_domain_bus_and_slot()</code>	Find <code>pci_dev</code> corresponding to given domain, bus and slot and number. If the device is found, its reference count is increased.
<code>pci_set_power_state()</code>	Set PCI Power Management state (0=D0 ... 3=D3)
<code>pci_find_capability()</code>	Find specified capability in device's capability list.
<code>pci_resource_start()</code>	Returns bus start address for a given PCI region
<code>pci_resource_end()</code>	Returns bus end address for a given PCI region
<code>pci_resource_len()</code>	Returns the byte length of a PCI region
<code>pci_set_drvdata()</code>	Set private driver data pointer for a <code>pci_dev</code>
<code>pci_get_drvdata()</code>	Return private driver data pointer for a <code>pci_dev</code>
<code>pci_set_mwi()</code>	Enable Memory-Write-Invalidate transactions.
<code>pci_clear_mwi()</code>	Disable Memory-Write-Invalidate transactions.

1.8 Miscellaneous hints

When displaying PCI device names to the user (for example when a driver wants to tell the user what card has it found), please use `pci_name(pci_dev)`.

Always refer to the PCI devices by a pointer to the `pci_dev` structure. All PCI layer functions use this identification and it's the only reasonable one. Don't use bus/slot/function numbers except for very special purposes -- on systems with multiple primary buses their semantics can be pretty complex.

Don't try to turn on Fast Back to Back writes in your driver. All devices on the bus need to be capable of doing it, so this is something which needs to be handled by platform and generic code, not individual drivers.

1.9 Vendor and device identifications

Do not add new device or vendor IDs to `include/linux/pci_ids.h` unless they are shared across multiple drivers. You can add private definitions in your driver if they're helpful, or just use plain hex constants.

The device IDs are arbitrary hex numbers (vendor controlled) and normally used only in a single location, the `pci_device_id` table.

Please DO submit new vendor/device IDs to <https://pci-ids.ucw.cz/>. There's a mirror of the `pci.ids` file at <https://github.com/pciutils/pciids>.

1.10 Obsolete functions

There are several functions which you might come across when trying to port an old driver to the new PCI interface. They are no longer present in the kernel as they aren't compatible with hotplug or PCI domains or having sane locking.

<code>pci_find_device()</code>	Superseded by <code>pci_get_device()</code>
<code>pci_find_subsys()</code>	Superseded by <code>pci_get_subsys()</code>
<code>pci_find_slot()</code>	Superseded by <code>pci_get_domain_bus_and_slot()</code>
<code>pci_get_slot()</code>	Superseded by <code>pci_get_domain_bus_and_slot()</code>

The alternative is the traditional PCI device driver that walks PCI device lists. This is still possible but discouraged.

1.11 MMIO Space and "Write Posting"

Converting a driver from using I/O Port space to using MMIO space often requires some additional changes. Specifically, "write posting" needs to be handled. Many drivers (e.g. tg3, acenic, sym53c8xx_2) already do this. I/O Port space guarantees write transactions reach the PCI device before the CPU can continue. Writes to MMIO space allow the CPU to continue before the transaction reaches the PCI device. HW weenies call this "Write Posting" because the write completion is "posted" to the CPU before the transaction has reached its destination.

Thus, timing sensitive code should add readl() where the CPU is expected to wait before doing other work. The classic "bit banging" sequence works fine for I/O Port space:

```
for (i = 8; --i; val >>= 1) {
    outb(val & 1, ioport_reg);      /* write bit */
    udelay(10);
}
```

The same sequence for MMIO space should be:

```
for (i = 8; --i; val >>= 1) {
    writeb(val & 1, mmio_reg);      /* write bit */
    readb(safe_mmio_reg);          /* flush posted write */
    udelay(10);
}
```

It is important that "safe_mmio_reg" not have any side effects that interferes with the correct operation of the device.

Another case to watch out for is when resetting a PCI device. Use PCI Configuration space reads to flush the writel(). This will gracefully handle the PCI master abort on all platforms if the PCI device is expected to not respond to a readl(). Most x86 platforms will allow MMIO reads to master abort (a.k.a. "Soft Fail") and return garbage (e.g. ~0). But many RISC platforms will crash (a.k.a."Hard Fail").

THE PCI EXPRESS PORT BUS DRIVER GUIDE HOWTO

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2.1 About this guide

This guide describes the basics of the PCI Express Port Bus driver and provides information on how to enable the service drivers to register/unregister with the PCI Express Port Bus Driver.

2.2 What is the PCI Express Port Bus Driver

A PCI Express Port is a logical PCI-PCI Bridge structure. There are two types of PCI Express Port: the Root Port and the Switch Port. The Root Port originates a PCI Express link from a PCI Express Root Complex and the Switch Port connects PCI Express links to internal logical PCI buses. The Switch Port, which has its secondary bus representing the switch's internal routing logic, is called the switch's Upstream Port. The switch's Downstream Port is bridging from switch's internal routing bus to a bus representing the downstream PCI Express link from the PCI Express Switch.

A PCI Express Port can provide up to four distinct functions, referred to in this document as services, depending on its port type. PCI Express Port's services include native hotplug support (HP), power management event support (PME), advanced error reporting support (AER), and virtual channel support (VC). These services may be handled by a single complex driver or be individually distributed and handled by corresponding service drivers.

2.3 Why use the PCI Express Port Bus Driver?

In existing Linux kernels, the Linux Device Driver Model allows a physical device to be handled by only a single driver. The PCI Express Port is a PCI-PCI Bridge device with multiple distinct services. To maintain a clean and simple solution each service may have its own software service driver. In this case several service drivers will compete for a single PCI-PCI Bridge device. For example, if the PCI Express Root Port native hotplug service driver is loaded first, it claims a PCI-PCI Bridge Root Port. The kernel therefore does not load other service drivers for that Root

Port. In other words, it is impossible to have multiple service drivers load and run on a PCI-PCI Bridge device simultaneously using the current driver model.

To enable multiple service drivers running simultaneously requires having a PCI Express Port Bus driver, which manages all populated PCI Express Ports and distributes all provided service requests to the corresponding service drivers as required. Some key advantages of using the PCI Express Port Bus driver are listed below:

- Allow multiple service drivers to run simultaneously on a PCI-PCI Bridge Port device.
- Allow service drivers implemented in an independent staged approach.
- Allow one service driver to run on multiple PCI-PCI Bridge Port devices.
- Manage and distribute resources of a PCI-PCI Bridge Port device to requested service drivers.

2.4 Configuring the PCI Express Port Bus Driver vs. Service Drivers

2.4.1 Including the PCI Express Port Bus Driver Support into the Kernel

Including the PCI Express Port Bus driver depends on whether the PCI Express support is included in the kernel config. The kernel will automatically include the PCI Express Port Bus driver as a kernel driver when the PCI Express support is enabled in the kernel.

2.4.2 Enabling Service Driver Support

PCI device drivers are implemented based on Linux Device Driver Model. All service drivers are PCI device drivers. As discussed above, it is impossible to load any service driver once the kernel has loaded the PCI Express Port Bus Driver. To meet the PCI Express Port Bus Driver Model requires some minimal changes on existing service drivers that imposes no impact on the functionality of existing service drivers.

A service driver is required to use the two APIs shown below to register its service with the PCI Express Port Bus driver (see section 5.2.1 & 5.2.2). It is important that a service driver initializes the `pcie_port_service_driver` data structure, included in header file `/include/linux/pcieport_if.h`, before calling these APIs. Failure to do so will result an identity mismatch, which prevents the PCI Express Port Bus driver from loading a service driver.

`pcie_port_service_register`

```
int pcie_port_service_register(struct pcie_port_service_driver *new)
```

This API replaces the Linux Driver Model's `pci_register_driver` API. A service driver should always calls `pcie_port_service_register` at module init. Note that after service driver being loaded, calls such as `pci_enable_device(dev)` and `pci_set_master(dev)` are no longer necessary since these calls are executed by the PCI Port Bus driver.

pcie_port_service_unregister

```
void pcie_port_service_unregister(struct pcie_port_service_driver *new)
```

pcie_port_service_unregister replaces the Linux Driver Model's pci_unregister_driver. It's always called by service driver when a module exits.

Sample Code

Below is sample service driver code to initialize the port service driver data structure.

```
static struct pcie_port_service_id service_id[] = { {
    .vendor = PCI_ANY_ID,
    .device = PCI_ANY_ID,
    .port_type = PCIE_RC_PORT,
    .service_type = PCIE_PORT_SERVICE_AER,
}, { /* end: all zeroes */ }
};

static struct pcie_port_service_driver root_aerdrv = {
    .name           = (char *)device_name,
    .id_table      = &service_id[0],
    .probe          = aerdrv_load,
    .remove         = aerdrv_unload,
    .suspend        = aerdrv_suspend,
    .resume         = aerdrv_resume,
};
```

Below is a sample code for registering/unregistering a service driver.

```
static int __init aerdrv_service_init(void)
{
    int retval = 0;

    retval = pcie_port_service_register(&root_aerdrv);
    if (!retval) {
        /*
         * FIX ME
         */
    }
    return retval;
}

static void __exit aerdrv_service_exit(void)
{
    pcie_port_service_unregister(&root_aerdrv);
}
```

```
module_init(aerdrv_service_init);
module_exit(aerdrv_service_exit);
```

2.5 Possible Resource Conflicts

Since all service drivers of a PCI-PCI Bridge Port device are allowed to run simultaneously, below lists a few of possible resource conflicts with proposed solutions.

2.5.1 MSI and MSI-X Vector Resource

Once MSI or MSI-X interrupts are enabled on a device, it stays in this mode until they are disabled again. Since service drivers of the same PCI-PCI Bridge port share the same physical device, if an individual service driver enables or disables MSI/MSI-X mode it may result unpredictable behavior.

To avoid this situation all service drivers are not permitted to switch interrupt mode on its device. The PCI Express Port Bus driver is responsible for determining the interrupt mode and this should be transparent to service drivers. Service drivers need to know only the vector IRQ assigned to the field irq of struct pcie_device, which is passed in when the PCI Express Port Bus driver probes each service driver. Service drivers should use (struct pcie_device*)dev->irq to call request_irq/free_irq. In addition, the interrupt mode is stored in the field interrupt_mode of struct pcie_device.

2.5.2 PCI Memory/IO Mapped Regions

Service drivers for PCI Express Power Management (PME), Advanced Error Reporting (AER), Hot-Plug (HP) and Virtual Channel (VC) access PCI configuration space on the PCI Express port. In all cases the registers accessed are independent of each other. This patch assumes that all service drivers will be well behaved and not overwrite other service driver's configuration settings.

2.5.3 PCI Config Registers

Each service driver runs its PCI config operations on its own capability structure except the PCI Express capability structure, that is shared between many drivers including the service drivers. RMW Capability accessors (pcie_capability_clear_and_set_word(), pcie_capability_set_word(), and pcie_capability_clear_word()) protect a selected set of PCI Express Capability Registers (Link Control Register and Root Control Register). Any change to those registers should be performed using RMW accessors to avoid problems due to concurrent updates. For the up-to-date list of protected registers, see pcie_capability_clear_and_set_word().

PCI EXPRESS I/O VIRTUALIZATION HOWTO

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3.1 Overview

3.1.1 What is SR-IOV

Single Root I/O Virtualization (SR-IOV) is a PCI Express Extended capability which makes one physical device appear as multiple virtual devices. The physical device is referred to as Physical Function (PF) while the virtual devices are referred to as Virtual Functions (VF). Allocation of the VF can be dynamically controlled by the PF via registers encapsulated in the capability. By default, this feature is not enabled and the PF behaves as traditional PCIe device. Once it's turned on, each VF's PCI configuration space can be accessed by its own Bus, Device and Function Number (Routing ID). And each VF also has PCI Memory Space, which is used to map its register set. VF device driver operates on the register set so it can be functional and appear as a real existing PCI device.

3.2 User Guide

3.2.1 How can I enable SR-IOV capability

Multiple methods are available for SR-IOV enablement. In the first method, the device driver (PF driver) will control the enabling and disabling of the capability via API provided by SR-IOV core. If the hardware has SR-IOV capability, loading its PF driver would enable it and all VFs associated with the PF. Some PF drivers require a module parameter to be set to determine the number of VFs to enable. In the second method, a write to the sysfs file `sriov_numvfs` will enable and disable the VFs associated with a PCIe PF. This method enables per-PF, VF enable/disable values versus the first method, which applies to all PFs of the same device. Additionally, the PCI SRIOV core support ensures that enable/disable operations are valid to reduce duplication in multiple drivers for the same checks, e.g., check `numvfs == 0` if enabling VFs, ensure `numvfs <= totalvfs`. The second method is the recommended method for new/future VF devices.

3.2.2 How can I use the Virtual Functions

The VF is treated as hot-plugged PCI devices in the kernel, so they should be able to work in the same way as real PCI devices. The VF requires device driver that is same as a normal PCI device's.

3.3 Developer Guide

3.3.1 SR-IOV API

To enable SR-IOV capability:

- (a) For the first method, in the driver:

```
int pci_enable_sriov(struct pci_dev *dev, int nr_virtfn);
```

'nr_virtfn' is number of VFs to be enabled.

- (b) For the second method, from sysfs:

```
echo 'nr_virtfn' > \
/sys/bus/pci/devices/<DOMAIN:BUS:DEVICE.FUNCTION>/sriov_numvfs
```

To disable SR-IOV capability:

- (a) For the first method, in the driver:

```
void pci_disable_sriov(struct pci_dev *dev);
```

- (b) For the second method, from sysfs:

```
echo 0 > \
/sys/bus/pci/devices/<DOMAIN:BUS:DEVICE.FUNCTION>/sriov_numvfs
```

To enable auto probing VFs by a compatible driver on the host, run command below before enabling SR-IOV capabilities. This is the default behavior.

```
echo 1 > \
/sys/bus/pci/devices/<DOMAIN:BUS:DEVICE.FUNCTION>/sriov_drivers_autoprobe
```

To disable auto probing VFs by a compatible driver on the host, run command below before enabling SR-IOV capabilities. Updating this entry will not affect VFs which are already probed.

```
echo 0 > \
/sys/bus/pci/devices/<DOMAIN:BUS:DEVICE.FUNCTION>/sriov_drivers_autoprobe
```

3.3.2 Usage example

Following piece of code illustrates the usage of the SR-IOV API.

```
static int dev_probe(struct pci_dev *dev, const struct pci_device_id *id)
{
    pci_enable_sriov(dev, NR_VIRTFN);

    ...

    return 0;
}

static void dev_remove(struct pci_dev *dev)
{
    pci_disable_sriov(dev);

    ...
}

static int dev_suspend(struct device *dev)
{
    ...

    return 0;
}

static int dev_resume(struct device *dev)
{
    ...

    return 0;
}

static void dev_shutdown(struct pci_dev *dev)
{
    ...
}

static int dev_sriov_configure(struct pci_dev *dev, int numvfs)
{
    if (numvfs > 0) {
        ...
        pci_enable_sriov(dev, numvfs);
        ...
        return numvfs;
    }
    if (numvfs == 0) {
        ...
        pci_disable_sriov(dev);
        ...
    }
}
```

```
        return 0;
    }

static struct pci_driver dev_driver = {
    .name =           "SR-IOV Physical Function driver",
    .id_table =       dev_id_table,
    .probe =          dev_probe,
    .remove =         dev_remove,
    .driver.pm =     &dev_pm_ops,
    .shutdown =       dev_shutdown,
    .sriov_configure = dev_sriov_configure,
};
```

THE MSI DRIVER GUIDE HOWTO

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4.1 About this guide

This guide describes the basics of Message Signaled Interrupts (MSIs), the advantages of using MSI over traditional interrupt mechanisms, how to change your driver to use MSI or MSI-X and some basic diagnostics to try if a device doesn't support MSIs.

4.2 What are MSIs?

A Message Signaled Interrupt is a write from the device to a special address which causes an interrupt to be received by the CPU.

The MSI capability was first specified in PCI 2.2 and was later enhanced in PCI 3.0 to allow each interrupt to be masked individually. The MSI-X capability was also introduced with PCI 3.0. It supports more interrupts per device than MSI and allows interrupts to be independently configured.

Devices may support both MSI and MSI-X, but only one can be enabled at a time.

4.3 Why use MSIs?

There are three reasons why using MSIs can give an advantage over traditional pin-based interrupts.

Pin-based PCI interrupts are often shared amongst several devices. To support this, the kernel must call each interrupt handler associated with an interrupt, which leads to reduced performance for the system as a whole. MSIs are never shared, so this problem cannot arise.

When a device writes data to memory, then raises a pin-based interrupt, it is possible that the interrupt may arrive before all the data has arrived in memory (this becomes more likely with devices behind PCI-PCI bridges). In order to ensure that all the data has arrived in memory, the interrupt handler must read a register on the device which raised the interrupt. PCI transaction ordering rules require that all the data arrive in memory before the value may be returned from

the register. Using MSIs avoids this problem as the interrupt-generating write cannot pass the data writes, so by the time the interrupt is raised, the driver knows that all the data has arrived in memory.

PCI devices can only support a single pin-based interrupt per function. Often drivers have to query the device to find out what event has occurred, slowing down interrupt handling for the common case. With MSIs, a device can support more interrupts, allowing each interrupt to be specialised to a different purpose. One possible design gives infrequent conditions (such as errors) their own interrupt which allows the driver to handle the normal interrupt handling path more efficiently. Other possible designs include giving one interrupt to each packet queue in a network card or each port in a storage controller.

4.4 How to use MSIs

PCI devices are initialised to use pin-based interrupts. The device driver has to set up the device to use MSI or MSI-X. Not all machines support MSIs correctly, and for those machines, the APIs described below will simply fail and the device will continue to use pin-based interrupts.

4.4.1 Include kernel support for MSIs

To support MSI or MSI-X, the kernel must be built with the CONFIG_PCI_MSI option enabled. This option is only available on some architectures, and it may depend on some other options also being set. For example, on x86, you must also enable X86_UP_APIC or SMP in order to see the CONFIG_PCI_MSI option.

4.4.2 Using MSI

Most of the hard work is done for the driver in the PCI layer. The driver simply has to request that the PCI layer set up the MSI capability for this device.

To automatically use MSI or MSI-X interrupt vectors, use the following function:

```
int pci_alloc_irq_vectors(struct pci_dev *dev, unsigned int min_vecs,
                           unsigned int max_vecs, unsigned int flags);
```

which allocates up to max_vecs interrupt vectors for a PCI device. It returns the number of vectors allocated or a negative error. If the device has a requirements for a minimum number of vectors the driver can pass a min_vecs argument set to this limit, and the PCI core will return -ENOSPC if it can't meet the minimum number of vectors.

The flags argument is used to specify which type of interrupt can be used by the device and the driver (PCI_IRQ_LEGACY, PCI_IRQ_MSI, PCI_IRQ_MSIX). A convenient short-hand (PCI_IRQ_ALL_TYPES) is also available to ask for any possible kind of interrupt. If the PCI_IRQ_AFFINITY flag is set, `pci_alloc_irq_vectors()` will spread the interrupts around the available CPUs.

To get the Linux IRQ numbers passed to `request_irq()` and `free_irq()` and the vectors, use the following function:

```
int pci_irq_vector(struct pci_dev *dev, unsigned int nr);
```

Any allocated resources should be freed before removing the device using the following function:

```
void pci_free_irq_vectors(struct pci_dev *dev);
```

If a device supports both MSI-X and MSI capabilities, this API will use the MSI-X facilities in preference to the MSI facilities. MSI-X supports any number of interrupts between 1 and 2048. In contrast, MSI is restricted to a maximum of 32 interrupts (and must be a power of two). In addition, the MSI interrupt vectors must be allocated consecutively, so the system might not be able to allocate as many vectors for MSI as it could for MSI-X. On some platforms, MSI interrupts must all be targeted at the same set of CPUs whereas MSI-X interrupts can all be targeted at different CPUs.

If a device supports neither MSI-X or MSI it will fall back to a single legacy IRQ vector.

The typical usage of MSI or MSI-X interrupts is to allocate as many vectors as possible, likely up to the limit supported by the device. If nvec is larger than the number supported by the device it will automatically be capped to the supported limit, so there is no need to query the number of vectors supported beforehand:

```
nvec = pci_alloc_irq_vectors(pdev, 1, nvec, PCI_IRQ_ALL_TYPES)
if (nvec < 0)
    goto out_err;
```

If a driver is unable or unwilling to deal with a variable number of MSI interrupts it can request a particular number of interrupts by passing that number to `pci_alloc_irq_vectors()` function as both 'min_vecs' and 'max_vecs' parameters:

```
ret = pci_alloc_irq_vectors(pdev, nvec, nvec, PCI_IRQ_ALL_TYPES);
if (ret < 0)
    goto out_err;
```

The most notorious example of the request type described above is enabling the single MSI mode for a device. It could be done by passing two 1s as 'min_vecs' and 'max_vecs':

```
ret = pci_alloc_irq_vectors(pdev, 1, 1, PCI_IRQ_ALL_TYPES);
if (ret < 0)
    goto out_err;
```

Some devices might not support using legacy line interrupts, in which case the driver can specify that only MSI or MSI-X is acceptable:

```
nvec = pci_alloc_irq_vectors(pdev, 1, nvec, PCI_IRQ_MSI | PCI_IRQ_MSIX);
if (nvec < 0)
    goto out_err;
```

4.4.3 Legacy APIs

The following old APIs to enable and disable MSI or MSI-X interrupts should not be used in new code:

```
pci_enable_msi()          /* deprecated */
pci_disable_msi()         /* deprecated */
pci_enable_msix_range()   /* deprecated */
pci_enable_msix_exact()   /* deprecated */
pci_disable_msix()        /* deprecated */
```

Additionally there are APIs to provide the number of supported MSI or MSI-X vectors: `pci_msi_vec_count()` and `pci_msix_vec_count()`. In general these should be avoided in favor of letting `pci_alloc_irq_vectors()` cap the number of vectors. If you have a legitimate special use case for the count of vectors we might have to revisit that decision and add a `pci_nr_irq_vectors()` helper that handles MSI and MSI-X transparently.

4.4.4 Considerations when using MSIs

Spinlocks

Most device drivers have a per-device spinlock which is taken in the interrupt handler. With pin-based interrupts or a single MSI, it is not necessary to disable interrupts (Linux guarantees the same interrupt will not be re-entered). If a device uses multiple interrupts, the driver must disable interrupts while the lock is held. If the device sends a different interrupt, the driver will deadlock trying to recursively acquire the spinlock. Such deadlocks can be avoided by using `spin_lock_irqsave()` or `spin_lock_irq()` which disable local interrupts and acquire the lock (see Documentation/kernel-hacking/locking.rst).

4.4.5 How to tell whether MSI/MSI-X is enabled on a device

Using 'lspci -v' (as root) may show some devices with "MSI", "Message Signalled Interrupts" or "MSI-X" capabilities. Each of these capabilities has an 'Enable' flag which is followed with either "+" (enabled) or "-" (disabled).

4.5 MSI quirks

Several PCI chipsets or devices are known not to support MSIs. The PCI stack provides three ways to disable MSIs:

1. globally
2. on all devices behind a specific bridge
3. on a single device

4.5.1 Disabling MSIs globally

Some host chipsets simply don't support MSIs properly. If we're lucky, the manufacturer knows this and has indicated it in the ACPI FADT table. In this case, Linux automatically disables MSIs. Some boards don't include this information in the table and so we have to detect them ourselves. The complete list of these is found near the `quirk_disable_all_msi()` function in `drivers/pci/quirks.c`.

If you have a board which has problems with MSIs, you can pass `pci=nomsi` on the kernel command line to disable MSIs on all devices. It would be in your best interests to report the problem to linux-pci@vger.kernel.org including a full '`lspci -v`' so we can add the quirks to the kernel.

4.5.2 Disabling MSIs below a bridge

Some PCI bridges are not able to route MSIs between buses properly. In this case, MSIs must be disabled on all devices behind the bridge.

Some bridges allow you to enable MSIs by changing some bits in their PCI configuration space (especially the Hypertransport chipsets such as the nVidia nForce and Serverworks HT2000). As with host chipsets, Linux mostly knows about them and automatically enables MSIs if it can. If you have a bridge unknown to Linux, you can enable MSIs in configuration space using whatever method you know works, then enable MSIs on that bridge by doing:

```
echo 1 > /sys/bus/pci/devices/$bridge/msi_bus
```

where `$bridge` is the PCI address of the bridge you've enabled (eg `0000:00:0e.0`).

To disable MSIs, echo 0 instead of 1. Changing this value should be done with caution as it could break interrupt handling for all devices below this bridge.

Again, please notify linux-pci@vger.kernel.org of any bridges that need special handling.

4.5.3 Disabling MSIs on a single device

Some devices are known to have faulty MSI implementations. Usually this is handled in the individual device driver, but occasionally it's necessary to handle this with a quirk. Some drivers have an option to disable use of MSI. While this is a convenient workaround for the driver author, it is not good practice, and should not be emulated.

4.5.4 Finding why MSIs are disabled on a device

From the above three sections, you can see that there are many reasons why MSIs may not be enabled for a given device. Your first step should be to examine your `dmesg` carefully to determine whether MSIs are enabled for your machine. You should also check your `.config` to be sure you have enabled `CONFIG_PCI_MSI`.

Then, '`lspci -t`' gives the list of bridges above a device. Reading `/sys/bus/pci/devices/*/msi_bus` will tell you whether MSIs are enabled (1) or disabled (0). If 0 is found in any of the `msi_bus` files belonging to bridges between the PCI root and the device, MSIs are disabled.

It is also worth checking the device driver to see whether it supports MSIs. For example, it may contain calls to `pci_alloc_irq_vectors()` with the `PCI_IRQ_MSI` or `PCI_IRQ_MSIX` flags.

4.6 List of device drivers MSI(-X) APIs

The PCI/MSI subsystem has a dedicated C file for its exported device driver APIs — *drivers/pci/msi/api.c*. The following functions are exported:

int pci_enable_msi(struct pci_dev *dev)

Enable MSI interrupt mode on device

Parameters

struct pci_dev *dev

the PCI device to operate on

Description

Legacy device driver API to enable MSI interrupts mode on device and allocate a single interrupt vector. On success, the allocated vector Linux IRQ will be saved at **dev->irq**. The driver must invoke *pci_disable_msi()* on cleanup.

NOTE

The newer *pci_alloc_irq_vectors()* / *pci_free_irq_vectors()* API pair should, in general, be used instead.

Return

0 on success, errno otherwise

void pci_disable_msi(struct pci_dev *dev)

Disable MSI interrupt mode on device

Parameters

struct pci_dev *dev

the PCI device to operate on

Description

Legacy device driver API to disable MSI interrupt mode on device, free earlier allocated interrupt vectors, and restore INTx emulation. The PCI device Linux IRQ (**dev->irq**) is restored to its default pin-assertion IRQ. This is the cleanup pair of *pci_enable_msi()*.

NOTE

The newer *pci_alloc_irq_vectors()* / *pci_free_irq_vectors()* API pair should, in general, be used instead.

int pci_msix_vec_count(struct pci_dev *dev)

Get number of MSI-X interrupt vectors on device

Parameters

struct pci_dev *dev

the PCI device to operate on

Return

number of MSI-X interrupt vectors available on this device (i.e., the device's MSI-X capability structure "table size"), -EINVAL if the device is not MSI-X capable, other errnos otherwise.

```
int pci_enable_msix_range(struct pci_dev *dev, struct msix_entry *entries, int minvec, int maxvec)
```

Enable MSI-X interrupt mode on device

Parameters

struct pci_dev *dev

the PCI device to operate on

struct msix_entry *entries

input/output parameter, array of MSI-X configuration entries

int minvec

minimum required number of MSI-X vectors

int maxvec

maximum desired number of MSI-X vectors

Description

Legacy device driver API to enable MSI-X interrupt mode on device and configure its MSI-X capability structure as appropriate. The passed **entries** array must have each of its members "entry" field set to a desired (valid) MSI-X vector number, where the range of valid MSI-X vector numbers can be queried through [*pci_msix_vec_count\(\)*](#). If successful, the driver must invoke [*pci_disable_msix\(\)*](#) on cleanup.

NOTE

The newer [*pci_alloc_irq_vectors\(\)*](#) / [*pci_free_irq_vectors\(\)*](#) API pair should, in general, be used instead.

Return

number of MSI-X vectors allocated (which might be smaller than **maxvecs**), where Linux IRQ numbers for such allocated vectors are saved back in the **entries** array elements' "vector" field. Return -ENOSPC if less than **minvecs** interrupt vectors are available. Return -EINVAL if one of the passed **entries** members "entry" field was invalid or a duplicate, or if plain MSI interrupts mode was earlier enabled on device. Return other errnos otherwise.

bool pci_msix_can_alloc_dyn(struct pci_dev *dev)

Query whether dynamic allocation after enabling MSI-X is supported

Parameters

struct pci_dev *dev

PCI device to operate on

Return

True if supported, false otherwise

struct msi_map pci_msix_alloc_irq_at(struct pci_dev *dev, unsigned int index, const struct irq_affinity_desc *affdesc)

Allocate an MSI-X interrupt after enabling MSI-X at a given MSI-X vector index or any free vector index

Parameters

struct pci_dev *dev

PCI device to operate on

unsigned int index

Index to allocate. If **index** == MSI_ANY_INDEX this allocates the next free index in the MSI-X table

const struct irq_affinity_desc *affdesc

Optional pointer to an affinity descriptor structure. NULL otherwise

Return

A struct msi_map

On success msi_map::index contains the allocated index (≥ 0) and msi_map::irq contains the allocated Linux interrupt number (> 0).

On fail msi_map::index contains the error code and msi_map::irq is set to 0.

void pci_msix_free_irq(struct pci_dev *dev, struct msi_map map)

Free an interrupt on a PCI/MSIX interrupt domain

Parameters**struct pci_dev *dev**

The PCI device to operate on

struct msi_map map

A struct msi_map describing the interrupt to free

Description

Undo an interrupt vector allocation. Does not disable MSI-X.

void pci_disable_msix(struct pci_dev *dev)

Disable MSI-X interrupt mode on device

Parameters**struct pci_dev *dev**

the PCI device to operate on

Description

Legacy device driver API to disable MSI-X interrupt mode on device, free earlier-allocated interrupt vectors, and restore INTx. The PCI device Linux IRQ (**dev->irq**) is restored to its default pin assertion IRQ. This is the cleanup pair of [*pci_enable_msix_range\(\)*](#).

NOTE

The newer [*pci_alloc_irq_vectors\(\)*](#) / [*pci_free_irq_vectors\(\)*](#) API pair should, in general, be used instead.

int pci_alloc_irq_vectors(struct pci_dev *dev, unsigned int min_vecs, unsigned int max_vecs, unsigned int flags)

Allocate multiple device interrupt vectors

Parameters**struct pci_dev *dev**

the PCI device to operate on

unsigned int min_vecs

minimum required number of vectors (must be ≥ 1)

unsigned int max_vecs

maximum desired number of vectors

unsigned int flags

One or more of:

- PCI_IRQ_MSIX Allow trying MSI-X vector allocations
- PCI_IRQ_MSI Allow trying MSI vector allocations
- PCI_IRQ_LEGACY Allow trying legacy INTx interrupts, if and only if **min_vecs** == 1
- PCI_IRQ_AFFINITY Auto-manage IRQs affinity by spreading the vectors around available CPUs

Description

Allocate up to **max_vecs** interrupt vectors on device. MSI-X irq vector allocation has a higher precedence over plain MSI, which has a higher precedence over legacy INTx emulation.

Upon a successful allocation, the caller should use [*pci_irq_vector\(\)*](#) to get the Linux IRQ number to be passed to [*request_threaded_irq\(\)*](#). The driver must call [*pci_free_irq_vectors\(\)*](#) on cleanup.

Return

number of allocated vectors (which might be smaller than **max_vecs**), -ENOSPC if less than **min_vecs** interrupt vectors are available, other errnos otherwise.

```
int pci_alloc_irq_vectors_affinity(struct pci_dev *dev, unsigned int min_vecs, unsigned
                                    int max_vecs, unsigned int flags, struct irq_affinity
                                    *affd)
```

Allocate multiple device interrupt vectors with affinity requirements

Parameters**struct pci_dev *dev**

the PCI device to operate on

unsigned int min_vecs

minimum required number of vectors (must be ≥ 1)

unsigned int max_vecs

maximum desired number of vectors

unsigned int flags

allocation flags, as in [*pci_alloc_irq_vectors\(\)*](#)

struct irq_affinity *affd

affinity requirements (can be NULL).

Description

Same as [*pci_alloc_irq_vectors\(\)*](#), but with the extra **affd** parameter. Check that function docs, and [*struct irq_affinity*](#), for more details.

```
int pci_irq_vector(struct pci_dev *dev, unsigned int nr)
```

Get Linux IRQ number of a device interrupt vector

Parameters

```
struct pci_dev *dev
```

the PCI device to operate on

unsigned int nr

device-relative interrupt vector index (0-based); has different meanings, depending on interrupt mode:

- MSI-X the index in the MSI-X vector table
 - MSI the index of the enabled MSI vectors
 - INTx must be 0

Return

the Linux IRQ number, or -EINVAL if **nr** is out of range

```
const struct cpumask *pci_irq_get_affinity(struct pci_dev *dev, int nr)
```

Get a device interrupt vector affinity

Parameters

```
struct pci_dev *dev
```

the PCI device to operate on

int nr

device-relative interrupt vector index (0-based); has different meanings, depending on interrupt mode:

- MSI-X the index in the MSI-X vector table
 - MSI the index of the enabled MSI vectors
 - INTx must be 0

Return

MSI/MSI-X vector affinity, NULL if **nr** is out of range or if the MSI(-X) vector was allocated without explicit affinity requirements (e.g., by `pci_enable_msi()`, `pci_enable_msix_range()`, or `pci_alloc_irq_vectors()` without the PCI_IRQ_AFFINITY flag). Return a generic set of CPU IDs representing all possible CPUs available during system boot if the device is in legacy INTx mode.

```
struct msi_map pci_ims_alloc_irq(struct pci_dev *dev, union msi_instance_cookie *icookie,  
                                const struct irq_affinity_desc *affdesc)
```

Allocate an interrupt on a PCI/IMS interrupt domain

Parameters

```
struct pci_dev *dev
```

The PCI device to operate on

```
union msi_instance_cookie *icookie
```

Pointer to an IMS implementation specific cookie for this IMS instance (PASID, queue ID, pointer...). The cookie content is copied into the MSI descriptor for the interrupt chip callbacks or domain specific setup functions.

```
const struct irq affinity desc *affdesc
```

Optional pointer to an interrupt affinity descriptor

Description

There is no index for IMS allocations as IMS is an implementation specific storage and does not have any direct associations between index, which might be a pure software construct, and device functionality. This association is established by the driver either via the index - if there is a hardware table - or in case of purely software managed IMS implementation the association happens via the `irq_write_msi_msg()` callback of the implementation specific interrupt chip, which utilizes the provided **icookie** to store the MSI message in the appropriate place.

Return

A struct `msi_map`

On success `msi_map::index` contains the allocated index (≥ 0) and `msi_map::virq` the allocated Linux interrupt number (> 0).

On fail `msi_map::index` contains the error code and `msi_map::virq` is set to 0.

void `pci_ims_free_irq`(struct pci_dev *dev, struct msi_map map)

Allocate an interrupt on a PCI/IMS interrupt domain which was allocated via `pci_ims_alloc_irq()`

Parameters

struct pci_dev *dev

The PCI device to operate on

struct msi_map map

A struct `msi_map` describing the interrupt to free as returned from `pci_ims_alloc_irq()`

void `pci_free_irq_vectors`(struct pci_dev *dev)

Free previously allocated IRQs for a device

Parameters

struct pci_dev *dev

the PCI device to operate on

Description

Undo the interrupt vector allocations and possible device MSI/MSI-X enablement earlier done through `pci_alloc_irq_vectors_affinity()` or `pci_alloc_irq_vectors()`.

void `pci_restore_msi_state`(struct pci_dev *dev)

Restore cached MSI(-X) state on device

Parameters

struct pci_dev *dev

the PCI device to operate on

Description

Write the Linux-cached MSI(-X) state back on device. This is typically useful upon system resume, or after an error-recovery PCI adapter reset.

int `pci_msi_enabled`(void)

Are MSI(-X) interrupts enabled system-wide?

Parameters

void

no arguments

Return

true if MSI has not been globally disabled through ACPI FADT, PCI bridge quirks, or the "pci=nomsi" kernel command-line option.

ACCESSING PCI DEVICE RESOURCES THROUGH SYSFS

sysfs, usually mounted at /sys, provides access to PCI resources on platforms that support it. For example, a given bus might look like this:

```
/sys/devices/pci0000:17
|-- 0000:17:00.0
|   |-- class
|   |-- config
|   |-- device
|   |-- enable
|   |-- irq
|   |-- local_cpus
|   |-- remove
|   |-- resource
|   |-- resource0
|   |-- resource1
|   |-- resource2
|   |-- revision
|   |-- rom
|   |-- subsystem_device
|   |-- subsystem_vendor
|   `-- vendor
|
`-- ...
```

The topmost element describes the PCI domain and bus number. In this case, the domain number is 0000 and the bus number is 17 (both values are in hex). This bus contains a single function device in slot 0. The domain and bus numbers are reproduced for convenience. Under the device directory are several files, each with their own function.

file	function
class	PCI class (ascii, ro)
config	PCI config space (binary, rw)
device	PCI device (ascii, ro)
enable	Whether the device is enabled (ascii, rw)
irq	IRQ number (ascii, ro)
local_cpus	nearby CPU mask (cpumask, ro)
remove	remove device from kernel's list (ascii, wo)
resource	PCI resource host addresses (ascii, ro)
resource0..N	PCI resource N, if present (binary, mmap, rw ¹)
resource0_wc..N_wc	PCI WC map resource N, if prefetchable (binary, mmap)
revision	PCI revision (ascii, ro)
rom	PCI ROM resource, if present (binary, ro)
subsystem_device	PCI subsystem device (ascii, ro)
subsystem_vendor	PCI subsystem vendor (ascii, ro)
vendor	PCI vendor (ascii, ro)

```

ro - read only file
rw - file is readable and writable
wo - write only file
mmap - file is mmapable
ascii - file contains ascii text
binary - file contains binary data
cpumask - file contains a cpumask type

```

The read only files are informational, writes to them will be ignored, with the exception of the 'rom' file. Writable files can be used to perform actions on the device (e.g. changing config space, detaching a device). mmapable files are available via an mmap of the file at offset 0 and can be used to do actual device programming from userspace. Note that some platforms don't support mmapping of certain resources, so be sure to check the return value from any attempted mmap. The most notable of these are I/O port resources, which also provide read/write access.

The 'enable' file provides a counter that indicates how many times the device has been enabled. If the 'enable' file currently returns '4', and a '1' is echoed into it, it will then return '5'. Echoing a '0' into it will decrease the count. Even when it returns to 0, though, some of the initialisation may not be reversed.

The 'rom' file is special in that it provides read-only access to the device's ROM file, if available. It's disabled by default, however, so applications should write the string "1" to the file to enable it before attempting a read call, and disable it following the access by writing "0" to the file. Note that the device must be enabled for a rom read to return data successfully. In the event a driver is not bound to the device, it can be enabled using the 'enable' file, documented above.

The 'remove' file is used to remove the PCI device, by writing a non-zero integer to the file. This does not involve any kind of hot-plug functionality, e.g. powering off the device. The device is removed from the kernel's list of PCI devices, the sysfs directory for it is removed, and the device will be removed from any drivers attached to it. Removal of PCI root buses is disallowed.

¹ rw for IORESOURCE_IO (I/O port) regions only

5.1 Accessing legacy resources through sysfs

Legacy I/O port and ISA memory resources are also provided in sysfs if the underlying platform supports them. They're located in the PCI class hierarchy, e.g.:

```
/sys/class/pci_bus/0000:17/
|-- bridge -> ../../devices/pci0000:17
|-- cpufreq
|-- legacy_io
`-- legacy_mem
```

The legacy_io file is a read/write file that can be used by applications to do legacy port I/O. The application should open the file, seek to the desired port (e.g. 0x3e8) and do a read or a write of 1, 2 or 4 bytes. The legacy_mem file should be mmaped with an offset corresponding to the memory offset desired, e.g. 0xa0000 for the VGA frame buffer. The application can then simply dereference the returned pointer (after checking for errors of course) to access legacy memory space.

5.2 Supporting PCI access on new platforms

In order to support PCI resource mapping as described above, Linux platform code should ideally define ARCH_GENERIC_PCI_MMAP_RESOURCE and use the generic implementation of that functionality. To support the historical interface of mmap() through files in /proc/bus/pci, platforms may also set HAVE_PCI_MMAP.

Alternatively, platforms which set HAVE_PCI_MMAP may provide their own implementation of pci_mmap_resource_range() instead of defining ARCH_GENERIC_PCI_MMAP_RESOURCE.

Platforms which support write-combining maps of PCI resources must define arch_can_pci_mmap_wc() which shall evaluate to non-zero at runtime when write-combining is permitted. Platforms which support maps of I/O resources define arch_can_pci_mmap_io() similarly.

Legacy resources are protected by the HAVE_PCI_LEGACY define. Platforms wishing to support legacy functionality should define it and provide pci_legacy_read, pci_legacy_write and pci_mmap_legacy_page_range functions.

ACPI CONSIDERATIONS FOR PCI HOST BRIDGES

The general rule is that the ACPI namespace should describe everything the OS might use unless there's another way for the OS to find it [1, 2].

For example, there's no standard hardware mechanism for enumerating PCI host bridges, so the ACPI namespace must describe each host bridge, the method for accessing PCI config space below it, the address space windows the host bridge forwards to PCI (using `_CRS`), and the routing of legacy INTx interrupts (using `_PRT`).

PCI devices, which are below the host bridge, generally do not need to be described via ACPI. The OS can discover them via the standard PCI enumeration mechanism, using config accesses to discover and identify devices and read and size their BARs. However, ACPI may describe PCI devices if it provides power management or hotplug functionality for them or if the device has INTx interrupts connected by platform interrupt controllers and a `_PRT` is needed to describe those connections.

ACPI resource description is done via `_CRS` objects of devices in the ACPI namespace [2]. The `_CRS` is like a generalized PCI BAR: the OS can read `_CRS` and figure out what resource is being consumed even if it doesn't have a driver for the device [3]. That's important because it means an old OS can work correctly even on a system with new devices unknown to the OS. The new devices might not do anything, but the OS can at least make sure no resources conflict with them.

Static tables like MCFG, HPET, ECDT, etc., are *not* mechanisms for reserving address space. The static tables are for things the OS needs to know early in boot, before it can parse the ACPI namespace. If a new table is defined, an old OS needs to operate correctly even though it ignores the table. `_CRS` allows that because it is generic and understood by the old OS; a static table does not.

If the OS is expected to manage a non-discoverable device described via ACPI, that device will have a specific `_HID/_CID` that tells the OS what driver to bind to it, and the `_CRS` tells the OS and the driver where the device's registers are.

PCI host bridges are PNP0A03 or PNP0A08 devices. Their `_CRS` should describe all the address space they consume. This includes all the windows they forward down to the PCI bus, as well as registers of the host bridge itself that are not forwarded to PCI. The host bridge registers include things like secondary/subordinate bus registers that determine the bus range below the bridge, window registers that describe the apertures, etc. These are all device-specific, non-architected things, so the only way a PNP0A03/PNP0A08 driver can manage them is via `_PRS/_CRS/_SRS`, which contain the device-specific details. The host bridge registers also include ECAM space, since it is consumed by the host bridge.

ACPI defines a Consumer/Producer bit to distinguish the bridge registers ("Consumer") from the bridge apertures ("Producer") [4, 5], but early BIOSes didn't use that bit correctly. The

result is that the current ACPI spec defines Consumer/Producer only for the Extended Address Space descriptors; the bit should be ignored in the older QWord/DWord/Word Address Space descriptors. Consequently, OSes have to assume all QWord/DWord/Word descriptors are windows.

Prior to the addition of Extended Address Space descriptors, the failure of Consumer/Producer meant there was no way to describe bridge registers in the PNP0A03/PNP0A08 device itself. The workaround was to describe the bridge registers (including ECAM space) in PNP0C02 catch-all devices [6]. With the exception of ECAM, the bridge register space is device-specific anyway, so the generic PNP0A03/PNP0A08 driver (`pci_root.c`) has no need to know about it.

New architectures should be able to use "Consumer" Extended Address Space descriptors in the PNP0A03 device for bridge registers, including ECAM, although a strict interpretation of [6] might prohibit this. Old x86 and ia64 kernels assume all address space descriptors, including "Consumer" Extended Address Space ones, are windows, so it would not be safe to describe bridge registers this way on those architectures.

PNP0C02 "motherboard" devices are basically a catch-all. There's no programming model for them other than "don't use these resources for anything else." So a PNP0C02 _CRS should claim any address space that is (1) not claimed by _CRS under any other device object in the ACPI namespace and (2) should not be assigned by the OS to something else.

The PCIe spec requires the Enhanced Configuration Access Method (ECAM) unless there's a standard firmware interface for config access, e.g., the ia64 SAL interface [7]. A host bridge consumes ECAM memory address space and converts memory accesses into PCI configuration accesses. The spec defines the ECAM address space layout and functionality; only the base of the address space is device-specific. An ACPI OS learns the base address from either the static MCFG table or a _CBA method in the PNP0A03 device.

The MCFG table must describe the ECAM space of non-hot pluggable host bridges [8]. Since MCFG is a static table and can't be updated by hotplug, a _CBA method in the PNP0A03 device describes the ECAM space of a hot-pluggable host bridge [9]. Note that for both MCFG and _CBA, the base address always corresponds to bus 0, even if the bus range below the bridge (which is reported via _CRS) doesn't start at 0.

[1] ACPI 6.2, sec 6.1:

For any device that is on a non-enumerable type of bus (for example, an ISA bus), OSPM enumerates the devices' identifier(s) and the ACPI system firmware must supply an _HID object ... for each device to enable OSPM to do that.

[2] ACPI 6.2, sec 3.7:

The OS enumerates motherboard devices simply by reading through the ACPI Namespace looking for devices with hardware IDs.

Each device enumerated by ACPI includes ACPI-defined objects in the ACPI Namespace that report the hardware resources the device could occupy [_PRS], an object that reports the resources that are currently used by the device [_CRS], and objects for configuring those resources [_SRS]. The information is used by the Plug and Play OS (OSPM) to configure the devices.

[3] ACPI 6.2, sec 6.2:

OSPM uses device configuration objects to configure hardware resources for devices enumerated via ACPI. Device configuration objects provide information about current and possible resource requirements, the relationship between shared resources, and methods for configuring hardware resources.

When OSPM enumerates a device, it calls _PRS to determine the resource requirements of the device. It may also call _CRS to find the current resource settings for the device. Using this information, the Plug and Play system determines what resources the device should consume and sets those resources by calling the device's _SRS control method.

In ACPI, devices can consume resources (for example, legacy keyboards), provide resources (for example, a proprietary PCI bridge), or do both. Unless otherwise specified, resources for a device are assumed to be taken from the nearest matching resource above the device in the device hierarchy.

[4] ACPI 6.2, sec 6.4.3.5.1, 2, 3, 4:

QWord/DWord/Word Address Space Descriptor (.1, .2, .3)

General Flags: Bit [0] Ignored

Extended Address Space Descriptor (.4)

General Flags: Bit [0] Consumer/Producer:

- 1 – This device consumes this resource
- 0 – This device produces and consumes this resource

[5] ACPI 6.2, sec 19.6.43:

ResourceUsage specifies whether the Memory range is consumed by this device (ResourceConsumer) or passed on to child devices (ResourceProducer). If nothing is specified, then ResourceConsumer is assumed.

[6] PCI Firmware 3.2, sec 4.1.2:

If the operating system does not natively comprehend reserving the MMCFG region, the MMCFG region must be reserved by firmware. The address range reported in the MCFG table or by _CBA method (see Section 4.1.3) must be reserved by declaring a motherboard resource. For most systems, the motherboard resource would appear at the root of the ACPI namespace (under _SB) in a node with a _HID of EISAID (PNP0C02), and the resources in this case should not be claimed in the root PCI bus's _CRS. The resources can optionally be returned in Int15 E820 or EFIGetMemoryMap as reserved memory but must always be reported through ACPI as a motherboard resource.

[7] PCI Express 4.0, sec 7.2.2:

For systems that are PC-compatible, or that do not implement a processor-architecture-specific firmware interface standard that allows access to the Configuration Space, the ECAM is required as defined in this section.

[8] PCI Firmware 3.2, sec 4.1.2:

The MCFG table is an ACPI table that is used to communicate the base addresses corresponding to the non-hot removable PCI Segment Groups range within a PCI Segment Group available to the operating system at boot. This is required for the PC-compatible systems.

The MCFG table is only used to communicate the base addresses corresponding to the PCI Segment Groups available to the system at boot.

[9] PCI Firmware 3.2, sec 4.1.3:

The _CBA (Memory mapped Configuration Base Address) control method is an optional ACPI object that returns the 64-bit memory mapped configuration base address for the hot plug capable host bridge. The base address returned by _CBA is processor-relative address. The _CBA control method evaluates to an Integer.

This control method appears under a host bridge object. When the _CBA method appears under an active host bridge object, the operating system evaluates this structure to identify the memory mapped configuration base address corresponding to the PCI Segment Group for the bus number range specified in _CRS method. An ACPI name space object that contains the _CBA method must also contain a corresponding _SEG method.

PCI ERROR RECOVERY

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Many PCI bus controllers are able to detect a variety of hardware PCI errors on the bus, such as parity errors on the data and address buses, as well as SERR and PERR errors. Some of the more advanced chipsets are able to deal with these errors; these include PCI-E chipsets, and the PCI-host bridges found on IBM Power4, Power5 and Power6-based pSeries boxes. A typical action taken is to disconnect the affected device, halting all I/O to it. The goal of a disconnection is to avoid system corruption; for example, to halt system memory corruption due to DMAs to "wild" addresses. Typically, a reconnection mechanism is also offered, so that the affected PCI device(s) are reset and put back into working condition. The reset phase requires coordination between the affected device drivers and the PCI controller chip. This document describes a generic API for notifying device drivers of a bus disconnection, and then performing error recovery. This API is currently implemented in the 2.6.16 and later kernels.

Reporting and recovery is performed in several steps. First, when a PCI hardware error has resulted in a bus disconnect, that event is reported as soon as possible to all affected device drivers, including multiple instances of a device driver on multi-function cards. This allows device drivers to avoid deadlocking in spinloops, waiting for some i/o-space register to change, when it never will. It also gives the drivers a chance to defer incoming I/O as needed.

Next, recovery is performed in several stages. Most of the complexity is forced by the need to handle multi-function devices, that is, devices that have multiple device drivers associated with them. In the first stage, each driver is allowed to indicate what type of reset it desires, the choices being a simple re-enabling of I/O or requesting a slot reset.

If any driver requests a slot reset, that is what will be done.

After a reset and/or a re-enabling of I/O, all drivers are again notified, so that they may then perform any device setup/config that may be required. After these have all completed, a final "resume normal operations" event is sent out.

The biggest reason for choosing a kernel-based implementation rather than a user-space implementation was the need to deal with bus disconnects of PCI devices attached to storage media, and, in particular, disconnects from devices holding the root file system. If the root file system is disconnected, a user-space mechanism would have to go through a large number of contortions to complete recovery. Almost all of the current Linux file systems are not tolerant of disconnection from/reconnection to their underlying block device. By contrast, bus errors are easy to manage in the device driver. Indeed, most device drivers already handle very similar recovery

procedures; for example, the SCSI-generic layer already provides significant mechanisms for dealing with SCSI bus errors and SCSI bus resets.

7.1 Detailed Design

Design and implementation details below, based on a chain of public email discussions with Ben Herrenschmidt, circa 5 April 2005.

The error recovery API support is exposed to the driver in the form of a structure of function pointers pointed to by a new field in *struct pci_driver*. A driver that fails to provide the structure is "non-aware", and the actual recovery steps taken are platform dependent. The arch/powerpc implementation will simulate a PCI hotplug remove/add.

This structure has the form:

```
struct pci_error_handlers
{
    int (*error_detected)(struct pci_dev *dev, pci_channel_state_t);
    int (*mmio_enabled)(struct pci_dev *dev);
    int (*slot_reset)(struct pci_dev *dev);
    void (*resume)(struct pci_dev *dev);
    void (*cor_error_detected)(struct pci_dev *dev);
};
```

The possible channel states are:

```
typedef enum {
    pci_channel_io_normal, /* I/O channel is in normal state */
    pci_channel_io_frozen, /* I/O to channel is blocked */
    pci_channel_io_perm_failure, /* PCI card is dead */
} pci_channel_state_t;
```

Possible return values are:

```
enum pci_ers_result {
    PCI_ERS_RESULT_NONE,          /* no result/none/not supported in device */
    PCI_ERS_RESULT_CAN_RECOVER,   /* Device driver can recover without slot */
    PCI_ERS_RESULT_NEED_RESET,    /* Device driver wants slot to be reset. */
    PCI_ERS_RESULT_DISCONNECT,    /* Device has completely failed, is */
    PCI_ERS_RESULT_RECOVERED,     /* Device driver is fully recovered and */
};
```

A driver does not have to implement all of these callbacks; however, if it implements any, it must implement *error_detected()*. If a callback is not implemented, the corresponding feature is considered unsupported. For example, if *mmio_enabled()* and *resume()* aren't there, then it is assumed that the driver is not doing any direct recovery and requires a *slot_reset()*. Typically a driver will want to know about a *slot_reset()*.

The actual steps taken by a platform to recover from a PCI error event will be platform-dependent, but will follow the general sequence described below.

7.1.1 STEP 0: Error Event

A PCI bus error is detected by the PCI hardware. On powerpc, the slot is isolated, in that all I/O is blocked: all reads return 0xffffffff, all writes are ignored.

7.1.2 STEP 1: Notification

Platform calls the `error_detected()` callback on every instance of every driver affected by the error.

At this point, the device might not be accessible anymore, depending on the platform (the slot will be isolated on powerpc). The driver may already have "noticed" the error because of a failing I/O, but this is the proper "synchronization point", that is, it gives the driver a chance to cleanup, waiting for pending stuff (timers, whatever, etc...) to complete; it can take semaphores, schedule, etc... everything but touch the device. Within this function and after it returns, the driver shouldn't do any new IOs. Called in task context. This is sort of a "quiesce" point. See note about interrupts at the end of this doc.

All drivers participating in this system must implement this call. The driver must return one of the following result codes:

- **PCI_ERS_RESULT_CAN_RECOVER**

Driver returns this if it thinks it might be able to recover the HW by just banging IOs or if it wants to be given a chance to extract some diagnostic information (see `mmio_enable`, below).

- **PCI_ERS_RESULT_NEED_RESET**

Driver returns this if it can't recover without a slot reset.

- **PCI_ERS_RESULT_DISCONNECT**

Driver returns this if it doesn't want to recover at all.

The next step taken will depend on the result codes returned by the drivers.

If all drivers on the segment/slot return `PCI_ERS_RESULT_CAN_RECOVER`, then the platform should re-enable IOs on the slot (or do nothing in particular, if the platform doesn't isolate slots), and recovery proceeds to STEP 2 (MMIO Enable).

If any driver requested a slot reset (by returning `PCI_ERS_RESULT_NEED_RESET`), then recovery proceeds to STEP 4 (Slot Reset).

If the platform is unable to recover the slot, the next step is STEP 6 (Permanent Failure).

Note: The current powerpc implementation assumes that a device driver will *not* schedule or semaphore in this routine; the current powerpc implementation uses one kernel thread to notify all devices; thus, if one device sleeps/schedules, all devices are affected. Doing better requires complex multi-threaded logic in the error recovery implementation (e.g. waiting for all notification threads to "join" before proceeding with recovery.) This seems excessively complex and not worth implementing.

The current powerpc implementation doesn't much care if the device attempts I/O at this point, or not. I/Os will fail, returning a value of 0xff on read, and writes will be dropped. If more than EEH_MAX_FAILS I/Os are attempted to a frozen adapter, EEH assumes that the device driver has gone into an infinite loop and prints an error to syslog. A reboot is then required to get the device working again.

7.1.3 STEP 2: MMIO Enabled

The platform re-enables MMIO to the device (but typically not the DMA), and then calls the mmio_enabled() callback on all affected device drivers.

This is the "early recovery" call. IOs are allowed again, but DMA is not, with some restrictions. This is NOT a callback for the driver to start operations again, only to peek/poke at the device, extract diagnostic information, if any, and eventually do things like trigger a device local reset or some such, but not restart operations. This callback is made if all drivers on a segment agree that they can try to recover and if no automatic link reset was performed by the HW. If the platform can't just re-enable IOs without a slot reset or a link reset, it will not call this callback, and instead will have gone directly to STEP 3 (Link Reset) or STEP 4 (Slot Reset)

Note: The following is proposed; no platform implements this yet: Proposal: All I/Os should be done synchronously from within this callback, errors triggered by them will be returned via the normal pci_check_whatever() API, no new error_detected() callback will be issued due to an error happening here. However, such an error might cause IOs to be re-blocked for the whole segment, and thus invalidate the recovery that other devices on the same segment might have done, forcing the whole segment into one of the next states, that is, link reset or slot reset.

The driver should return one of the following result codes:

- **PCI_ERS_RESULT_RECOVERED**

Driver returns this if it thinks the device is fully functional and thinks it is ready to start normal driver operations again. There is no guarantee that the driver will actually be allowed to proceed, as another driver on the same segment might have failed and thus triggered a slot reset on platforms that support it.

- **PCI_ERS_RESULT_NEED_RESET**

Driver returns this if it thinks the device is not recoverable in its current state and it needs a slot reset to proceed.

- **PCI_ERS_RESULT_DISCONNECT**

Same as above. Total failure, no recovery even after reset driver dead. (To be defined more precisely)

The next step taken depends on the results returned by the drivers. If all drivers returned PCI_ERS_RESULT_RECOVERED, then the platform proceeds to either STEP3 (Link Reset) or to STEP 5 (Resume Operations).

If any driver returned PCI_ERS_RESULT_NEED_RESET, then the platform proceeds to STEP 4 (Slot Reset)

7.1.4 STEP 3: Link Reset

The platform resets the link. This is a PCI-Express specific step and is done whenever a fatal error has been detected that can be "solved" by resetting the link.

7.1.5 STEP 4: Slot Reset

In response to a return value of PCI_ERS_RESULT_NEED_RESET, the platform will perform a slot reset on the requesting PCI device(s). The actual steps taken by a platform to perform a slot reset will be platform-dependent. Upon completion of slot reset, the platform will call the device slot_reset() callback.

Powerpc platforms implement two levels of slot reset: soft reset(default) and fundamental(optional) reset.

Powerpc soft reset consists of asserting the adapter #RST line and then restoring the PCI BARs and PCI configuration header to a state that is equivalent to what it would be after a fresh system power-on followed by power-on BIOS/system firmware initialization. Soft reset is also known as hot-reset.

Powerpc fundamental reset is supported by PCI Express cards only and results in device's state machines, hardware logic, port states and configuration registers to initialize to their default conditions.

For most PCI devices, a soft reset will be sufficient for recovery. Optional fundamental reset is provided to support a limited number of PCI Express devices for which a soft reset is not sufficient for recovery.

If the platform supports PCI hotplug, then the reset might be performed by toggling the slot electrical power off/on.

It is important for the platform to restore the PCI config space to the "fresh poweron" state, rather than the "last state". After a slot reset, the device driver will almost always use its standard device initialization routines, and an unusual config space setup may result in hung devices, kernel panics, or silent data corruption.

This call gives drivers the chance to re-initialize the hardware (re-download firmware, etc.). At this point, the driver may assume that the card is in a fresh state and is fully functional. The slot is unfrozen and the driver has full access to PCI config space, memory mapped I/O space and DMA. Interrupts (Legacy, MSI, or MSI-X) will also be available.

Drivers should not restart normal I/O processing operations at this point. If all device drivers report success on this callback, the platform will call resume() to complete the sequence, and let the driver restart normal I/O processing.

A driver can still return a critical failure for this function if it can't get the device operational after reset. If the platform previously tried a soft reset, it might now try a hard reset (power cycle) and then call slot_reset() again. If the device still can't be recovered, there is nothing more that can be done; the platform will typically report a "permanent failure" in such a case. The device will be considered "dead" in this case.

Drivers for multi-function cards will need to coordinate among themselves as to which driver instance will perform any "one-shot" or global device initialization. For example, the Symbios sym53cxx2 driver performs device init only from PCI function 0:

```
+     if (PCI_FUNC(pdev->devfn) == 0)
+         sym_reset_scsi_bus(np, 0);
```

Result codes:

- PCI_ERS_RESULT_DISCONNECT Same as above.

Drivers for PCI Express cards that require a fundamental reset must set the `needs_freset` bit in the `pci_dev` structure in their probe function. For example, the QLogic `qla2xxx` driver sets the `needs_freset` bit for certain PCI card types:

```
+     /* Set EEH reset type to fundamental if required by hba */
+     if (IS_QLA24XX(ha) || IS_QLA25XX(ha) || IS_QLA81XX(ha))
+         pdev->needs_freset = 1;
+
```

Platform proceeds either to STEP 5 (Resume Operations) or STEP 6 (Permanent Failure).

Note: The current powerpc implementation does not try a power-cycle reset if the driver returned PCI_ERS_RESULT_DISCONNECT. However, it probably should.

7.1.6 STEP 5: Resume Operations

The platform will call the `resume()` callback on all affected device drivers if all drivers on the segment have returned `PCI_ERS_RESULT_RECOVERED` from one of the 3 previous callbacks. The goal of this callback is to tell the driver to restart activity, that everything is back and running. This callback does not return a result code.

At this point, if a new error happens, the platform will restart a new error recovery sequence.

7.1.7 STEP 6: Permanent Failure

A "permanent failure" has occurred, and the platform cannot recover the device. The platform will call `error_detected()` with a `pci_channel_state_t` value of `pci_channel_io_perm_failure`.

The device driver should, at this point, assume the worst. It should cancel all pending I/O, refuse all new I/O, returning -EIO to higher layers. The device driver should then clean up all of its memory and remove itself from kernel operations, much as it would during system shutdown.

The platform will typically notify the system operator of the permanent failure in some way. If the device is hotplug-capable, the operator will probably want to remove and replace the device. Note, however, not all failures are truly "permanent". Some are caused by over-heating, some by a poorly seated card. Many PCI error events are caused by software bugs, e.g. DMAs to wild addresses or bogus split transactions due to programming errors. See the discussion in `Documentation/arch/powerpc/eeh-pci-error-recovery.rst` for additional detail on real-life experience of the causes of software errors.

7.1.8 Conclusion; General Remarks

The way the callbacks are called is platform policy. A platform with no slot reset capability may want to just "ignore" drivers that can't recover (disconnect them) and try to let other cards on the same segment recover. Keep in mind that in most real life cases, though, there will be only one driver per segment.

Now, a note about interrupts. If you get an interrupt and your device is dead or has been isolated, there is a problem :) The current policy is to turn this into a platform policy. That is, the recovery API only requires that:

- There is no guarantee that interrupt delivery can proceed from any device on the segment starting from the error detection and until the slot_reset callback is called, at which point interrupts are expected to be fully operational.
- There is no guarantee that interrupt delivery is stopped, that is, a driver that gets an interrupt after detecting an error, or that detects an error within the interrupt handler such that it prevents proper ack'ing of the interrupt (and thus removal of the source) should just return IRQ_NOTHANDLED. It's up to the platform to deal with that condition, typically by masking the IRQ source during the duration of the error handling. It is expected that the platform "knows" which interrupts are routed to error-management capable slots and can deal with temporarily disabling that IRQ number during error processing (this isn't terribly complex). That means some IRQ latency for other devices sharing the interrupt, but there is simply no other way. High end platforms aren't supposed to share interrupts between many devices anyway :)

Note: Implementation details for the powerpc platform are discussed in the file Documentation/arch/powerpc/eeh-pci-error-recovery.rst

As of this writing, there is a growing list of device drivers with patches implementing error recovery. Not all of these patches are in mainline yet. These may be used as "examples":

- drivers/scsi/iopr
- drivers/scsi/sym53c8xx_2
- drivers/scsi/qla2xxx
- drivers/scsi/lpfc
- drivers/next/bnx2.c
- drivers/next/e100.c
- drivers/net/e1000
- drivers/net/e1000e
- drivers/net/ixgbe
- drivers/net/cxgb3
- drivers/net/s2io.c

The cor_error_detected() callback is invoked in handle_error_source() when the error severity is "correctable". The callback is optional and allows additional logging to be done if desired. See example:

- drivers/cxl/pci.c

7.1.9 The End

THE PCI EXPRESS ADVANCED ERROR REPORTING DRIVER GUIDE HOWTO

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8.1 Overview

8.1.1 About this guide

This guide describes the basics of the PCI Express (PCIe) Advanced Error Reporting (AER) driver and provides information on how to use it, as well as how to enable the drivers of Endpoint devices to conform with the PCIe AER driver.

8.1.2 What is the PCIe AER Driver?

PCIe error signaling can occur on the PCIe link itself or on behalf of transactions initiated on the link. PCIe defines two error reporting paradigms: the baseline capability and the Advanced Error Reporting capability. The baseline capability is required of all PCIe components providing a minimum defined set of error reporting requirements. Advanced Error Reporting capability is implemented with a PCIe Advanced Error Reporting extended capability structure providing more robust error reporting.

The PCIe AER driver provides the infrastructure to support PCIe Advanced Error Reporting capability. The PCIe AER driver provides three basic functions:

- Gathers the comprehensive error information if errors occurred.
- Reports error to the users.
- Performs error recovery actions.

The AER driver only attaches to Root Ports and RCECs that support the PCIe AER capability.

8.2 User Guide

8.2.1 Include the PCIe AER Root Driver into the Linux Kernel

The PCIe AER driver is a Root Port service driver attached via the PCIe Port Bus driver. If a user wants to use it, the driver must be compiled. It is enabled with CONFIG_PCIEAER, which depends on CONFIG_PCIEPORTBUS.

8.2.2 Load PCIe AER Root Driver

Some systems have AER support in firmware. Enabling Linux AER support at the same time the firmware handles AER would result in unpredictable behavior. Therefore, Linux does not handle AER events unless the firmware grants AER control to the OS via the ACPI_OSC method. See the PCI Firmware Specification for details regarding _OSC usage.

8.2.3 AER error output

When a PCIe AER error is captured, an error message will be output to console. If it's a correctable error, it is output as an info message. Otherwise, it is printed as an error. So users could choose different log level to filter out correctable error messages.

Below shows an example:

```
0000:50:00.0: PCIe Bus Error: severity=Uncorrected (Fatal), type=Transaction Layer, id=0500(Requester ID)
0000:50:00.0:    device [8086:0329] error status/mask=00100000/00000000
0000:50:00.0:    [20] Unsupported Request (First)
0000:50:00.0:    TLP Header: 04000001 00200a03 05010000 00050100
```

In the example, 'Requester ID' means the ID of the device that sent the error message to the Root Port. Please refer to PCIe specs for other fields.

8.2.4 AER Statistics / Counters

When PCIe AER errors are captured, the counters / statistics are also exposed in the form of sysfs attributes which are documented at Documentation/ABI/testing/sysfs-bus-pci-devices-aer_stats

8.3 Developer Guide

To enable error recovery, a software driver must provide callbacks.

To support AER better, developers need to understand how AER works.

PCIe errors are classified into two types: correctable errors and uncorrectable errors. This classification is based on the impact of those errors, which may result in degraded performance or function failure.

Correctable errors pose no impacts on the functionality of the interface. The PCIe protocol can recover without any software intervention or any loss of data. These errors are detected and corrected by hardware.

Unlike correctable errors, uncorrectable errors impact functionality of the interface. Uncorrectable errors can cause a particular transaction or a particular PCIe link to be unreliable. Depending on those error conditions, uncorrectable errors are further classified into non-fatal errors and fatal errors. Non-fatal errors cause the particular transaction to be unreliable, but the PCIe link itself is fully functional. Fatal errors, on the other hand, cause the link to be unreliable.

When PCIe error reporting is enabled, a device will automatically send an error message to the Root Port above it when it captures an error. The Root Port, upon receiving an error reporting message, internally processes and logs the error message in its AER Capability structure. Error information being logged includes storing the error reporting agent's requestor ID into the Error Source Identification Registers and setting the error bits of the Root Error Status Register accordingly. If AER error reporting is enabled in the Root Error Command Register, the Root Port generates an interrupt when an error is detected.

Note that the errors as described above are related to the PCIe hierarchy and links. These errors do not include any device specific errors because device specific errors will still get sent directly to the device driver.

8.3.1 Provide callbacks

callback reset_link to reset PCIe link

This callback is used to reset the PCIe physical link when a fatal error happens. The Root Port AER service driver provides a default `reset_link` function, but different Upstream Ports might have different specifications to reset the PCIe link, so Upstream Port drivers may provide their own `reset_link` functions.

Section 3.2.2.2 provides more detailed info on when to call `reset_link`.

PCI error-recovery callbacks

The PCIe AER Root driver uses error callbacks to coordinate with downstream device drivers associated with a hierarchy in question when performing error recovery actions.

Data `struct pci_driver` has a pointer, `err_handler`, to point to `pci_error_handlers` who consists of a couple of callback function pointers. The AER driver follows the rules defined in [PCI Error Recovery](#) except PCIe-specific parts (e.g. `reset_link`). Please refer to [PCI Error Recovery](#) for detailed definitions of the callbacks.

The sections below specify when to call the error callback functions.

Correctable errors

Correctable errors pose no impacts on the functionality of the interface. The PCIe protocol can recover without any software intervention or any loss of data. These errors do not require any recovery actions. The AER driver clears the device's correctable error status register accordingly and logs these errors.

Non-correctable (non-fatal and fatal) errors

If an error message indicates a non-fatal error, performing link reset at upstream is not required. The AER driver calls `error_detected(dev, pci_channel_io_normal)` to all drivers associated within a hierarchy in question. For example:

```
Endpoint <==> Downstream Port B <==> Upstream Port A <==> Root Port
```

If Upstream Port A captures an AER error, the hierarchy consists of Downstream Port B and Endpoint.

A driver may return `PCI_ERS_RESULT_CAN_RECOVER`, `PCI_ERS_RESULT_DISCONNECT`, or `PCI_ERS_RESULT_NEED_RESET`, depending on whether it can recover or the AER driver calls `mmio_enabled` as next.

If an error message indicates a fatal error, kernel will broadcast `error_detected(dev, pci_channel_io_frozen)` to all drivers within a hierarchy in question. Then, performing link reset at upstream is necessary. As different kinds of devices might use different approaches to reset link, AER port service driver is required to provide the function to reset link via callback parameter of `pcie_do_recovery()` function. If `reset_link` is not `NULL`, recovery function will use it to reset the link. If `error_detected` returns `PCI_ERS_RESULT_CAN_RECOVER` and `reset_link` returns `PCI_ERS_RESULT_RECOVERED`, the error handling goes to `mmio_enabled`.

8.3.2 Frequent Asked Questions

Q:

What happens if a PCIe device driver does not provide an error recovery handler (`pci_driver->err_handler` is equal to `NULL`)?

A:

The devices attached with the driver won't be recovered. If the error is fatal, kernel will print out warning messages. Please refer to section 3 for more information.

Q:

What happens if an upstream port service driver does not provide callback `reset_link`?

A:

Fatal error recovery will fail if the errors are reported by the upstream ports who are attached by the service driver.

8.4 Software error injection

Debugging PCIe AER error recovery code is quite difficult because it is hard to trigger real hardware errors. Software based error injection can be used to fake various kinds of PCIe errors.

First you should enable PCIe AER software error injection in kernel configuration, that is, following item should be in your .config.

CONFIG_PCIEAER_INJECT=y or CONFIG_PCIEAER_INJECT=m

After reboot with new kernel or insert the module, a device file named /dev/aer_inject should be created.

Then, you need a user space tool named aer-inject, which can be gotten from:

<https://git.kernel.org/cgit/linux/kernel/git/gong.chen/aer-inject.git/>

More information about aer-inject can be found in the document in its source code.

PCI ENDPOINT FRAMEWORK

This document is a guide to use the PCI Endpoint Framework in order to create endpoint controller driver, endpoint function driver, and using configfs interface to bind the function driver to the controller driver.

9.1 Introduction

Linux has a comprehensive PCI subsystem to support PCI controllers that operates in Root Complex mode. The subsystem has capability to scan PCI bus, assign memory resources and IRQ resources, load PCI driver (based on vendor ID, device ID), support other services like hot-plug, power management, advanced error reporting and virtual channels.

However the PCI controller IP integrated in some SoCs is capable of operating either in Root Complex mode or Endpoint mode. PCI Endpoint Framework will add endpoint mode support in Linux. This will help to run Linux in an EP system which can have a wide variety of use cases from testing or validation, co-processor accelerator, etc.

9.2 PCI Endpoint Core

The PCI Endpoint Core layer comprises 3 components: the Endpoint Controller library, the Endpoint Function library, and the configfs layer to bind the endpoint function with the endpoint controller.

9.2.1 PCI Endpoint Controller(EPC) Library

The EPC library provides APIs to be used by the controller that can operate in endpoint mode. It also provides APIs to be used by function driver/library in order to implement a particular endpoint function.

APIs for the PCI controller Driver

This section lists the APIs that the PCI Endpoint core provides to be used by the PCI controller driver.

- `devm_pci_epc_create()/pci_epc_create()`

The PCI controller driver should implement the following ops:

- `write_header`: ops to populate configuration space header
- `set_bar`: ops to configure the BAR
- `clear_bar`: ops to reset the BAR
- `alloc_addr_space`: ops to allocate in PCI controller address space
- `free_addr_space`: ops to free the allocated address space
- `raise_irq`: ops to raise a legacy, MSI or MSI-X interrupt
- `start`: ops to start the PCI link
- `stop`: ops to stop the PCI link

The PCI controller driver can then create a new EPC device by invoking `devm_pci_epc_create()/pci_epc_create()`.

- `devm_pci_epc_destroy()/pci_epc_destroy()`

The PCI controller driver can destroy the EPC device created by either `devm_pci_epc_create()` or `pci_epc_create()` using `devm_pci_epc_destroy()` or `pci_epc_destroy()`.

- `pci_epc_linkup()`

In order to notify all the function devices that the EPC device to which they are linked has established a link with the host, the PCI controller driver should invoke `pci_epc_linkup()`.

- `pci_epc_mem_init()`

Initialize the `pci_epc_mem` structure used for allocating EPC addr space.

- `pci_epc_mem_exit()`

Cleanup the `pci_epc_mem` structure allocated during `pci_epc_mem_init()`.

EPC APIs for the PCI Endpoint Function Driver

This section lists the APIs that the PCI Endpoint core provides to be used by the PCI endpoint function driver.

- `pci_epc_write_header()`

The PCI endpoint function driver should use `pci_epc_write_header()` to write the standard configuration header to the endpoint controller.

- `pci_epc_set_bar()`

The PCI endpoint function driver should use `pci_epc_set_bar()` to configure the Base Address Register in order for the host to assign PCI addr space. Register space of the function driver is usually configured using this API.

- `pci_epc_clear_bar()`

The PCI endpoint function driver should use `pci_epc_clear_bar()` to reset the BAR.

- `pci_epc_raise_irq()`

The PCI endpoint function driver should use `pci_epc_raise_irq()` to raise Legacy Interrupt, MSI or MSI-X Interrupt.

- `pci_epc_mem_alloc_addr()`

The PCI endpoint function driver should use `pci_epc_mem_alloc_addr()`, to allocate memory address from EPC addr space which is required to access RC's buffer

- `pci_epc_mem_free_addr()`

The PCI endpoint function driver should use `pci_epc_mem_free_addr()` to free the memory space allocated using `pci_epc_mem_alloc_addr()`.

Other EPC APIs

There are other APIs provided by the EPC library. These are used for binding the EPF device with EPC device. `pci-ep-cfs.c` can be used as reference for using these APIs.

- `pci_epc_get()`

Get a reference to the PCI endpoint controller based on the device name of the controller.

- `pci_epc_put()`

Release the reference to the PCI endpoint controller obtained using `pci_epc_get()`

- `pci_epc_add_epf()`

Add a PCI endpoint function to a PCI endpoint controller. A PCIe device can have up to 8 functions according to the specification.

- `pci_epc_remove_epf()`

Remove the PCI endpoint function from PCI endpoint controller.

- `pci_epc_start()`

The PCI endpoint function driver should invoke `pci_epc_start()` once it has configured the endpoint function and wants to start the PCI link.

- `pci_epc_stop()`

The PCI endpoint function driver should invoke `pci_epc_stop()` to stop the PCI LINK.

9.2.2 PCI Endpoint Function(EPF) Library

The EPF library provides APIs to be used by the function driver and the EPC library to provide endpoint mode functionality.

EPF APIs for the PCI Endpoint Function Driver

This section lists the APIs that the PCI Endpoint core provides to be used by the PCI endpoint function driver.

- `pci_epf_register_driver()`

The PCI Endpoint Function driver should implement the following ops:

- bind: ops to perform when a EPC device has been bound to EPF device
- unbind: ops to perform when a binding has been lost between a EPC device and EPF device
- linkup: ops to perform when the EPC device has established a connection with a host system

The PCI Function driver can then register the PCI EPF driver by using `pci_epf_register_driver()`.

- `pci_epf_unregister_driver()`

The PCI Function driver can unregister the PCI EPF driver by using `pci_epf_unregister_driver()`.

- `pci_epf_alloc_space()`

The PCI Function driver can allocate space for a particular BAR using `pci_epf_alloc_space()`.

- `pci_epf_free_space()`

The PCI Function driver can free the allocated space (using `pci_epf_alloc_space()`) by invoking `pci_epf_free_space()`.

APIs for the PCI Endpoint Controller Library

This section lists the APIs that the PCI Endpoint core provides to be used by the PCI endpoint controller library.

- `pci_epf_linkup()`

The PCI endpoint controller library invokes `pci_epf_linkup()` when the EPC device has established the connection to the host.

Other EPF APIs

There are other APIs provided by the EPF library. These are used to notify the function driver when the EPF device is bound to the EPC device. `pci-ep-cfs.c` can be used as reference for using these APIs.

- `pci_epf_create()`

Create a new PCI EPF device by passing the name of the PCI EPF device. This name will be used to bind the EPF device to a EPF driver.

- `pci_epf_destroy()`

Destroy the created PCI EPF device.

- `pci_epf_bind()`

`pci_epf_bind()` should be invoked when the EPF device has been bound to a EPC device.

- `pci_epf_unbind()`

`pci_epf_unbind()` should be invoked when the binding between EPC device and EPF device is lost.

9.3 Configuring PCI Endpoint Using CONFIGFS

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The PCI Endpoint Core exposes configfs entry (`pci_ep`) to configure the PCI endpoint function and to bind the endpoint function with the endpoint controller. (For introducing other mechanisms to configure the PCI Endpoint Function refer to [1]).

9.3.1 Mounting configfs

The PCI Endpoint Core layer creates `pci_ep` directory in the mounted configfs directory. configfs can be mounted using the following command:

```
mount -t configfs none /sys/kernel/config
```

9.3.2 Directory Structure

The `pci_ep` configfs has two directories at its root: `controllers` and `functions`. Every EPC device present in the system will have an entry in the `controllers` directory and every EPF driver present in the system will have an entry in the `functions` directory.

```
/sys/kernel/config/pci_ep/
    .. controllers/
    .. functions/
```

9.3.3 Creating EPF Device

Every registered EPF driver will be listed in controllers directory. The entries corresponding to EPF driver will be created by the EPF core.

```
/sys/kernel/config/pci_ep/functions/
    .. <EPF Driver1>/
        ... <EPF Device 11>/
        ... <EPF Device 21>/
        ... <EPF Device 31>/
    .. <EPF Driver2>/
        ... <EPF Device 12>/
        ... <EPF Device 22>/
```

In order to create a <EPF device> of the type probed by <EPF Driver>, the user has to create a directory inside <EPF DriverN>.

Every <EPF device> directory consists of the following entries that can be used to configure the standard configuration header of the endpoint function. (These entries are created by the framework when any new <EPF Device> is created)

```
.. <EPF Driver1>/
    ... <EPF Device 11>/
        ... vendorid
        ... deviceid
        ... revid
        ... progif_code
        ... subclass_code
        ... baseclass_code
        ... cache_line_size
        ... subsys_vendor_id
        ... subsys_id
        ... interrupt_pin
        ... <Symlink EPF Device 31>/
        ... primary/
            ... <Symlink EPC Device1>/
        ... secondary/
            ... <Symlink EPC Device2>/
```

If an EPF device has to be associated with 2 EPCs (like in the case of Non-transparent bridge), symlink of endpoint controller connected to primary interface should be added in 'primary' directory and symlink of endpoint controller connected to secondary interface should be added in 'secondary' directory.

The <EPF Device> directory can have a list of symbolic links (<Symlink EPF Device 31>) to other <EPF Device>. These symbolic links should be created by the user to represent the virtual functions that are bound to the physical function. In the above directory structure <EPF Device 11> is a physical function and <EPF Device 31> is a virtual function. An EPF device once it's linked to another EPF device, cannot be linked to a EPC device.

9.3.4 EPC Device

Every registered EPC device will be listed in controllers directory. The entries corresponding to EPC device will be created by the EPC core.

```
/sys/kernel/config/pci_ep/controllers/
  .. <EPC Device1>/
    ... <Symlink EPF Device11>/
    ... <Symlink EPF Device12>/
    ... start
  .. <EPC Device2>/
    ... <Symlink EPF Device21>/
    ... <Symlink EPF Device22>/
    ... start
```

The <EPC Device> directory will have a list of symbolic links to <EPF Device>. These symbolic links should be created by the user to represent the functions present in the endpoint device. Only <EPF Device> that represents a physical function can be linked to a EPC device.

The <EPC Device> directory will also have a *start* field. Once "1" is written to this field, the endpoint device will be ready to establish the link with the host. This is usually done after all the EPF devices are created and linked with the EPC device.

```
| controllers/
  | <Directory: EPC name>/
    | <Symbolic Link: Function>
    | start
| functions/
  | <Directory: EPF driver>/
    | <Directory: EPF device>/
      | vendorid
      | deviceid
      | revid
      | progif_code
      | subclass_code
      | baseclass_code
      | cache_line_size
      | subsys_vendor_id
      | subsys_id
      | interrupt_pin
      | function
```

[1] *Introduction*

9.4 PCI Test Function

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Traditionally PCI RC has always been validated by using standard PCI cards like ethernet PCI cards or USB PCI cards or SATA PCI cards. However with the addition of EP-core in linux kernel, it is possible to configure a PCI controller that can operate in EP mode to work as a test device.

The PCI endpoint test device is a virtual device (defined in software) used to test the endpoint functionality and serve as a sample driver for other PCI endpoint devices (to use the EP framework).

The PCI endpoint test device has the following registers:

- 1) PCI_ENDPOINT_TEST_MAGIC
- 2) PCI_ENDPOINT_TEST_COMMAND
- 3) PCI_ENDPOINT_TEST_STATUS
- 4) PCI_ENDPOINT_TEST_SRC_ADDR
- 5) PCI_ENDPOINT_TEST_DST_ADDR
- 6) PCI_ENDPOINT_TEST_SIZE
- 7) PCI_ENDPOINT_TEST_CHECKSUM
- 8) PCI_ENDPOINT_TEST_IRQ_TYPE
- 9) PCI_ENDPOINT_TEST_IRQ_NUMBER
 - PCI_ENDPOINT_TEST_MAGIC

This register will be used to test BAR0. A known pattern will be written and read back from MAGIC register to verify BAR0.

- PCI_ENDPOINT_TEST_COMMAND

This register will be used by the host driver to indicate the function that the endpoint device must perform.

Bitfield	Description
Bit 0	raise legacy IRQ
Bit 1	raise MSI IRQ
Bit 2	raise MSI-X IRQ
Bit 3	read command (read data from RC buffer)
Bit 4	write command (write data to RC buffer)
Bit 5	copy command (copy data from one RC buffer to another RC buffer)

- PCI_ENDPOINT_TEST_STATUS

This register reflects the status of the PCI endpoint device.

Bitfield	Description
Bit 0	read success
Bit 1	read fail
Bit 2	write success
Bit 3	write fail
Bit 4	copy success
Bit 5	copy fail
Bit 6	IRQ raised
Bit 7	source address is invalid
Bit 8	destination address is invalid

- PCI_ENDPOINT_TEST_SRC_ADDR

This register contains the source address (RC buffer address) for the COPY/READ command.

- PCI_ENDPOINT_TEST_DST_ADDR

This register contains the destination address (RC buffer address) for the COPY/WRITE command.

- PCI_ENDPOINT_TEST_IRQ_TYPE

This register contains the interrupt type (Legacy/MSI) triggered for the READ/WRITE/COPY and raise IRQ (Legacy/MSI) commands.

Possible types:

Legacy	0
MSI	1
MSI-X	2

- PCI_ENDPOINT_TEST_IRQ_NUMBER

This register contains the triggered ID interrupt.

Admissible values:

Legacy	0
MSI	[1 .. 32]
MSI-X	[1 .. 2048]

9.5 PCI Test User Guide

Author

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This document is a guide to help users use pci-epf-test function driver and pci_endpoint_test host driver for testing PCI. The list of steps to be followed in the host side and EP side is given below.

9.5.1 Endpoint Device

Endpoint Controller Devices

To find the list of endpoint controller devices in the system:

```
# ls /sys/class/pci_epc/
51000000.pcie_ep
```

If PCI_ENDPOINT_CONFIGFS is enabled:

```
# ls /sys/kernel/config/pci_ep/controllers
51000000.pcie_ep
```

Endpoint Function Drivers

To find the list of endpoint function drivers in the system:

```
# ls /sys/bus/pci-epf/drivers
pci_epf_test
```

If PCI_ENDPOINT_CONFIGFS is enabled:

```
# ls /sys/kernel/config/pci_ep/functions
pci_epf_test
```

Creating pci-epf-test Device

PCI endpoint function device can be created using the configfs. To create pci-epf-test device, the following commands can be used:

```
# mount -t configfs none /sys/kernel/config
# cd /sys/kernel/config/pci_ep/
# mkdir functions/pci_epf_test/func1
```

The "mkdir func1" above creates the pci-epf-test function device that will be probed by pci_epf_test driver.

The PCI endpoint framework populates the directory with the following configurable fields:

```
# ls functions/pci_epf_test/func1
baseclass_code      interrupt_pin    progif_code      subsys_id
cache_line_size    msi_interrupts  revid           subsys_vendorid
deviceid          msix_interrupts subclass_code   vendorid
```

The PCI endpoint function driver populates these entries with default values when the device is bound to the driver. The pci-epf-test driver populates vendorid with 0xffff and interrupt_pin with 0x0001:

```
# cat functions/pci_epf_test/func1/vendorid
0xffff
# cat functions/pci_epf_test/func1/interrupt_pin
0x0001
```

Configuring pci-epf-test Device

The user can configure the pci-epf-test device using configfs entry. In order to change the vendorid and the number of MSI interrupts used by the function device, the following commands can be used:

```
# echo 0x104c > functions/pci_epf_test/func1/vendorid
# echo 0xb500 > functions/pci_epf_test/func1/deviceid
# echo 16 > functions/pci_epf_test/func1/msi_interrupts
# echo 8 > functions/pci_epf_test/func1/msix_interrupts
```

Binding pci-epf-test Device to EP Controller

In order for the endpoint function device to be useful, it has to be bound to a PCI endpoint controller driver. Use the configfs to bind the function device to one of the controller driver present in the system:

```
# ln -s functions/pci_epf_test/func1 controllers/51000000.pcie_ep/
```

Once the above step is completed, the PCI endpoint is ready to establish a link with the host.

Start the Link

In order for the endpoint device to establish a link with the host, the `_start_` field should be populated with '1':

```
# echo 1 > controllers/51000000.pcie_ep/start
```

9.5.2 RootComplex Device

Ispci Output

Note that the devices listed here correspond to the value populated in 1.4 above:

```
00:00.0 PCI bridge: Texas Instruments Device 8888 (rev 01)
01:00.0 Unassigned class [ff00]: Texas Instruments Device b500
```

Using Endpoint Test function Device

pcitest.sh added in tools/pci/ can be used to run all the default PCI endpoint tests. To compile this tool the following commands should be used:

```
# cd <kernel-dir>
# make -C tools/pci
```

or if you desire to compile and install in your system:

```
# cd <kernel-dir>
# make -C tools/pci install
```

The tool and script will be located in <rootfs>/usr/bin/

pcitest.sh Output

```
# pcitest.sh
BAR tests

BAR0:          OKAY
BAR1:          OKAY
BAR2:          OKAY
BAR3:          OKAY
BAR4:          NOT OKAY
BAR5:          NOT OKAY

Interrupt tests

SET IRQ TYPE TO LEGACY:      OKAY
LEGACY IRQ:      NOT OKAY
SET IRQ TYPE TO MSI:        OKAY
MSI1:          OKAY
MSI2:          OKAY
MSI3:          OKAY
MSI4:          OKAY
MSI5:          OKAY
MSI6:          OKAY
MSI7:          OKAY
MSI8:          OKAY
MSI9:          OKAY
MSI10:         OKAY
MSI11:         OKAY
MSI12:         OKAY
MSI13:         OKAY
MSI14:         OKAY
MSI15:         OKAY
MSI16:         OKAY
MSI17:         NOT OKAY
MSI18:         NOT OKAY
```

```

MSI19:          NOT OKAY
MSI20:          NOT OKAY
MSI21:          NOT OKAY
MSI22:          NOT OKAY
MSI23:          NOT OKAY
MSI24:          NOT OKAY
MSI25:          NOT OKAY
MSI26:          NOT OKAY
MSI27:          NOT OKAY
MSI28:          NOT OKAY
MSI29:          NOT OKAY
MSI30:          NOT OKAY
MSI31:          NOT OKAY
MSI32:          NOT OKAY
SET IRQ TYPE TO MSI-X:      OKAY
MSI-X1:          OKAY
MSI-X2:          OKAY
MSI-X3:          OKAY
MSI-X4:          OKAY
MSI-X5:          OKAY
MSI-X6:          OKAY
MSI-X7:          OKAY
MSI-X8:          OKAY
MSI-X9:          NOT OKAY
MSI-X10:         NOT OKAY
MSI-X11:         NOT OKAY
MSI-X12:         NOT OKAY
MSI-X13:         NOT OKAY
MSI-X14:         NOT OKAY
MSI-X15:         NOT OKAY
MSI-X16:         NOT OKAY
[...]
MSI-X2047:       NOT OKAY
MSI-X2048:       NOT OKAY

```

Read Tests

```

SET IRQ TYPE TO MSI:      OKAY
READ (    1 bytes):      OKAY
READ (   1024 bytes):   OKAY
READ (   1025 bytes):   OKAY
READ (1024000 bytes):   OKAY
READ (1024001 bytes):   OKAY

```

Write Tests

```

WRITE (    1 bytes):     OKAY
WRITE (   1024 bytes):  OKAY
WRITE (   1025 bytes):  OKAY
WRITE (1024000 bytes):  OKAY

```

WRITE (1024001 bytes):	OKAY
------------------------	------

Copy Tests

COPY (1 bytes):	OKAY
COPY (1024 bytes):	OKAY
COPY (1025 bytes):	OKAY
COPY (1024000 bytes):	OKAY
COPY (1024001 bytes):	OKAY

9.6 PCI NTB Function

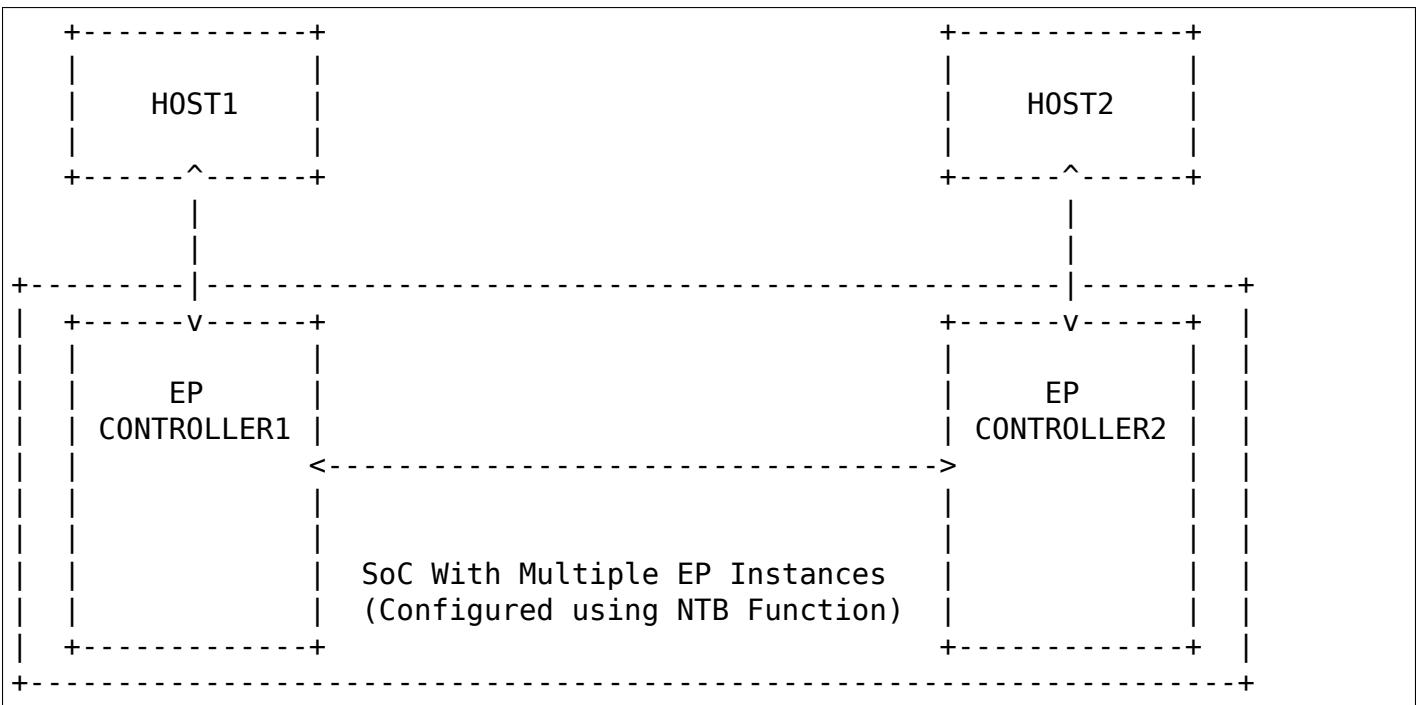
Author

Kishon Vijay Abraham I <kishon@ti.com>

PCI Non-Transparent Bridges (NTB) allow two host systems to communicate with each other by exposing each host as a device to the other host. NTBs typically support the ability to generate interrupts on the remote machine, expose memory ranges as BARs, and perform DMA. They also support scratchpads, which are areas of memory within the NTB that are accessible from both machines.

PCI NTB Function allows two different systems (or hosts) to communicate with each other by configuring the endpoint instances in such a way that transactions from one system are routed to the other system.

In the below diagram, PCI NTB function configures the SoC with multiple PCI Endpoint (EP) instances in such a way that transactions from one EP controller are routed to the other EP controller. Once PCI NTB function configures the SoC with multiple EP instances, HOST1 and HOST2 can communicate with each other using SoC as a bridge.



9.6.1 Constructs used for Implementing NTB

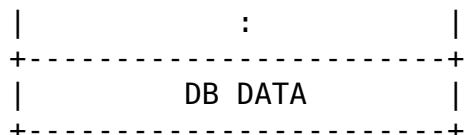
- 1) Config Region
- 2) Self Scratchpad Registers
- 3) Peer Scratchpad Registers
- 4) Doorbell (DB) Registers
- 5) Memory Window (MW)

Config Region:

Config Region is a construct that is specific to NTB implemented using NTB Endpoint Function Driver. The host and endpoint side NTB function driver will exchange information with each other using this region. Config Region has Control/Status Registers for configuring the Endpoint Controller. Host can write into this region for configuring the outbound Address Translation Unit (ATU) and to indicate the link status. Endpoint can indicate the status of commands issued by host in this region. Endpoint can also indicate the scratchpad offset and number of memory windows to the host using this region.

The format of Config Region is given below. All the fields here are 32 bits.

+	-----+
	COMMAND
+	-----+
	ARGUMENT
+	-----+
	STATUS
+	-----+
	TOPOLOGY
+	-----+
	ADDRESS (LOWER 32)
+	-----+
	ADDRESS (UPPER 32)
+	-----+
	SIZE
+	-----+
	NO OF MEMORY WINDOW
+	-----+
	MEMORY WINDOW1 OFFSET
+	-----+
	SPAD OFFSET
+	-----+
	SPAD COUNT
+	-----+
	DB ENTRY SIZE
+	-----+
	DB DATA
+	-----+
	:
+	-----+



COMMAND:

NTB function supports three commands:

CMD_CONFIGURE_DOORBELL (0x1): Command to configure doorbell. Before invoking this command, the host should allocate and initialize MSI/MSI-X vectors (i.e., initialize the MSI/MSI-X Capability in the Endpoint). The endpoint on receiving this command will configure the outbound ATU such that transactions to Doorbell BAR will be routed to the MSI/MSI-X address programmed by the host. The ARGUMENT register should be populated with number of DBs to configure (in the lower 16 bits) and if MSI or MSI-X should be configured (BIT 16).

CMD_CONFIGURE_MW (0x2): Command to configure memory window (MW). The host invokes this command after allocating a buffer that can be accessed by remote host. The allocated address should be programmed in the ADDRESS register (64 bit), the size should be programmed in the SIZE register and the memory window index should be programmed in the ARGUMENT register. The endpoint on receiving this command will configure the outbound ATU such that transactions to MW BAR are routed to the address provided by the host.

CMD_LINK_UP (0x3): Command to indicate an NTB application is bound to the EP device on the host side. Once the endpoint receives this command from both the hosts, the endpoint will raise a LINK_UP event to both the hosts to indicate the host NTB applications can start communicating with each other.

ARGUMENT:

The value of this register is based on the commands issued in command register. See COMMAND section for more information.

TOPOLOGY:

Set to NTB_TOPO_B2B_USD for Primary interface
Set to NTB_TOPO_B2B_DSD for Secondary interface

ADDRESS/SIZE:

Address and Size to be used while configuring the memory window.
See "CMD_CONFIGURE_MW" for more info.

MEMORY WINDOW1 OFFSET:

Memory Window 1 and Doorbell registers are packed together in the same BAR. The initial portion of the region will have doorbell registers and the latter portion of the region is for memory window 1. This register will specify the offset of the memory window 1.

NO OF MEMORY WINDOW:

Specifies the number of memory windows supported by the NTB device.

SPAD OFFSET:

Self scratchpad region and config region are packed together in the same BAR. The initial portion of the region will have config region and the latter portion of the region is for self scratchpad. This register will specify the offset of the self scratchpad registers.

SPAD COUNT:

Specifies the number of scratchpad registers supported by the NTB device.

DB ENTRY SIZE:

Used to determine the offset within the DB BAR that should be written in order to raise doorbell. EPF NTB can use either MSI or MSI-X to ring doorbell (MSI-X support will be added later). MSI uses same address for all the interrupts and MSI-X can provide different addresses for different interrupts. The MSI/MSI-X address is provided by the host and the address it gives is based on the MSI/MSI-X implementation supported by the host. For instance, ARM platform using GIC ITS will have the same MSI-X address for all the interrupts. In order to support all the combinations and use the same mechanism for both MSI and MSI-X, EPF NTB allocates a separate region in the Outbound Address Space for each of the interrupts. This region will be mapped to the MSI/MSI-X address provided by the host. If a host provides the same address for all the interrupts, all the regions will be translated to the same address. If a host provides different addresses, the regions will be translated to different addresses. This will ensure there is no difference while raising the doorbell.

DB DATA:

EPF NTB supports 32 interrupts, so there are 32 DB DATA registers. This holds the MSI/MSI-X data that has to be written to MSI address for raising doorbell interrupt. This will be populated by EPF NTB while invoking `CMD_CONFIGURE_DOORBELL`.

Scratchpad Registers:

Each host has its own register space allocated in the memory of NTB endpoint controller. They are both readable and writable from both sides of the bridge. They are used by applications built over NTB and can be used to pass control and status information between both sides of a device.

Scratchpad registers has 2 parts

- 1) Self Scratchpad: Host's own register space
- 2) Peer Scratchpad: Remote host's register space.

Doorbell Registers:

Doorbell Registers are used by the hosts to interrupt each other.

Memory Window:

Actual transfer of data between the two hosts will happen using the memory window.

9.6.2 Modeling Constructs:

There are 5 or more distinct regions (config, self scratchpad, peer scratchpad, doorbell, one or more memory windows) to be modeled to achieve NTB functionality. At least one memory window is required while more than one is permitted. All these regions should be mapped to BARs for hosts to access these regions.

If one 32-bit BAR is allocated for each of these regions, the scheme would look like this:

BAR NO	CONSTRUCTS USED
BAR0	Config Region
BAR1	Self Scratchpad
BAR2	Peer Scratchpad
BAR3	Doorbell
BAR4	Memory Window 1
BAR5	Memory Window 2

However if we allocate a separate BAR for each of the regions, there would not be enough BARs for all the regions in a platform that supports only 64-bit BARs.

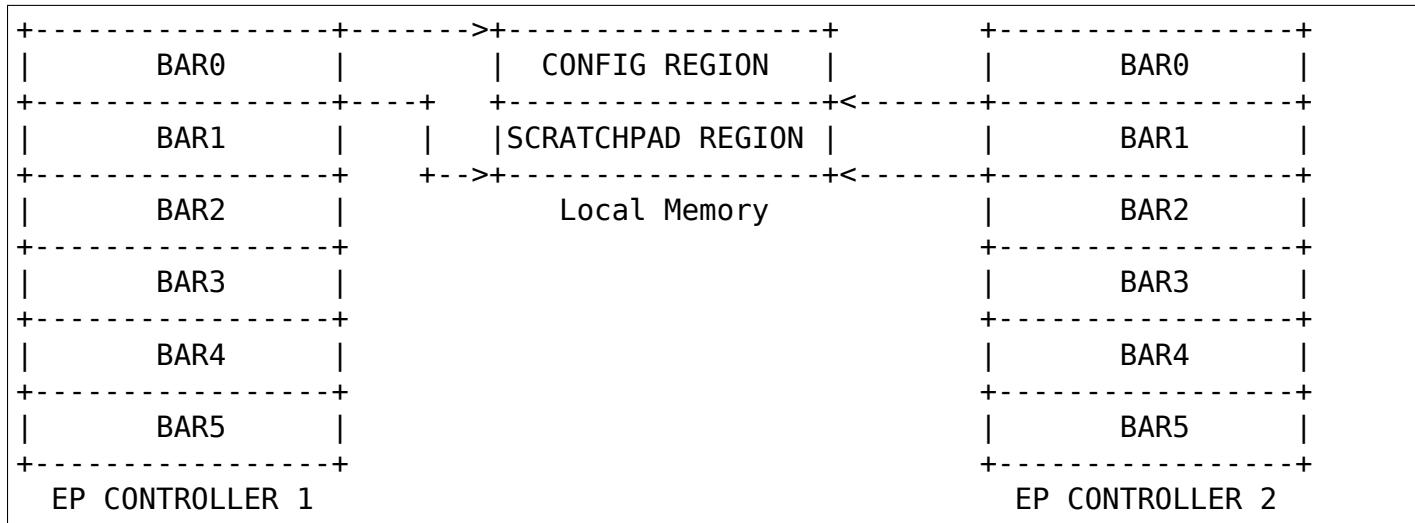
In order to be supported by most of the platforms, the regions should be packed and mapped to BARs in a way that provides NTB functionality and also makes sure the host doesn't access any region that it is not supposed to.

The following scheme is used in EPF NTB Function:

BAR NO	CONSTRUCTS USED
BAR0	Config Region + Self Scratchpad
BAR1	Peer Scratchpad
BAR2	Doorbell + Memory Window 1
BAR3	Memory Window 2
BAR4	Memory Window 3
BAR5	Memory Window 4

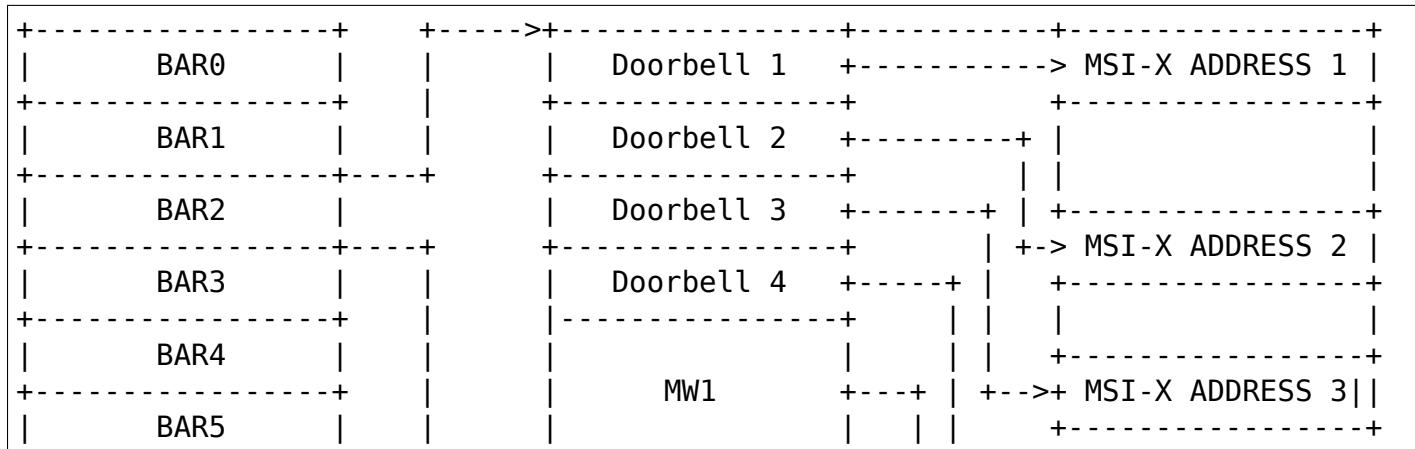
With this scheme, for the basic NTB functionality 3 BARs should be sufficient.

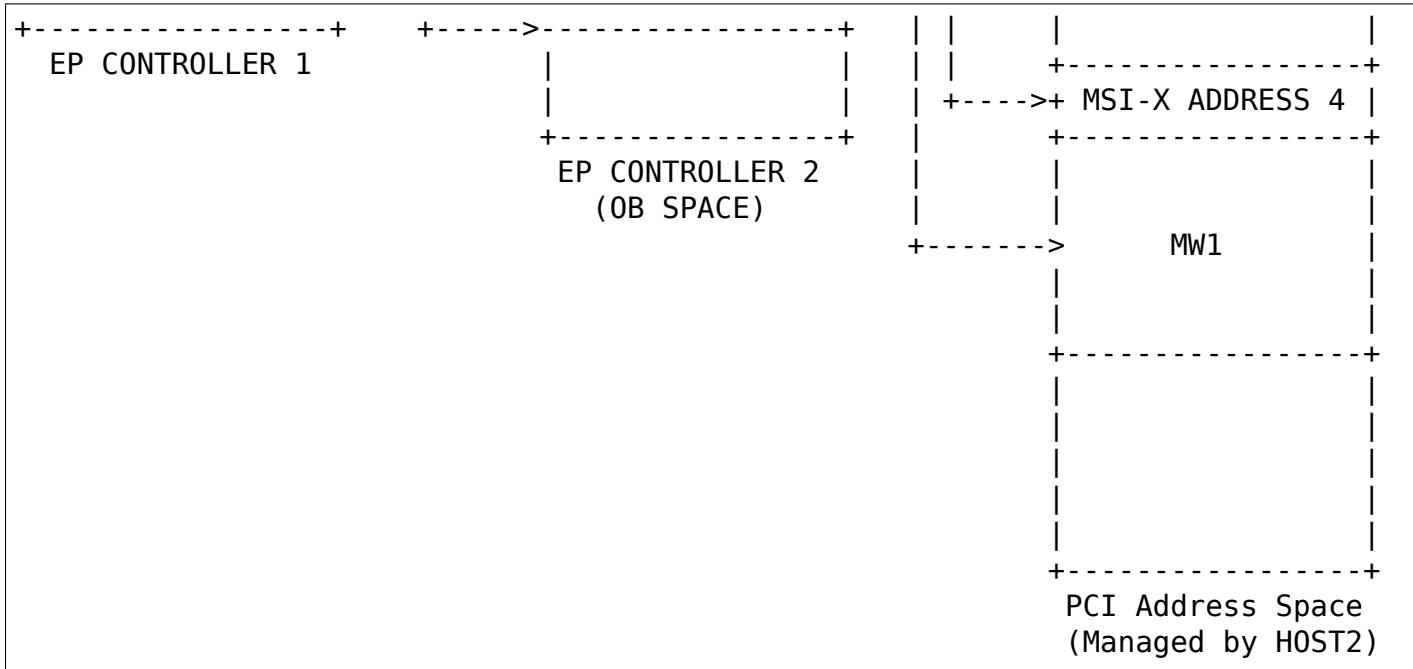
Modeling Config/Scratchpad Region:



Above diagram shows Config region + Scratchpad region for HOST1 (connected to EP controller 1) allocated in local memory. The HOST1 can access the config region and scratchpad region (self scratchpad) using BAR0 of EP controller 1. The peer host (HOST2 connected to EP controller 2) can also access this scratchpad region (peer scratchpad) using BAR1 of EP controller 2. This diagram shows the case where Config region and Scratchpad regions are allocated for HOST1, however the same is applicable for HOST2.

Modeling Doorbell/Memory Window 1:





Above diagram shows how the doorbell and memory window 1 is mapped so that HOST1 can raise doorbell interrupt on HOST2 and also how HOST1 can access buffers exposed by HOST2 using memory window1 (MW1). Here doorbell and memory window 1 regions are allocated in EP controller 2 outbound (OB) address space. Allocating and configuring BARs for doorbell and memory window1 is done during the initialization phase of NTB endpoint function driver. Mapping from EP controller 2 OB space to PCI address space is done when HOST2 sends CMD_CONFIGURE_MW/CMD_CONFIGURE_DOORBELL.

Modeling Optional Memory Windows:

This is modeled the same was as MW1 but each of the additional memory windows is mapped to separate BARs.

9.7 PCI Non-Transparent Bridge (NTB) Endpoint Function (EPF) User Guide

Author

Kishon Vijay Abraham I <kishon@ti.com>

This document is a guide to help users use pci-epf-ntb function driver and ntb_hw_epf host driver for NTB functionality. The list of steps to be followed in the host side and EP side is given below. For the hardware configuration and internals of NTB using configurable endpoints see [PCI NTB Function](#)

9.7.1 Endpoint Device

Endpoint Controller Devices

For implementing NTB functionality at least two endpoint controller devices are required.

To find the list of endpoint controller devices in the system:

```
# ls /sys/class/pci_epc/
2900000.pcie-ep  2910000.pcie-ep
```

If PCI_ENDPOINT_CONFIGFS is enabled:

```
# ls /sys/kernel/config/pci_ep/controllers
2900000.pcie-ep  2910000.pcie-ep
```

Endpoint Function Drivers

To find the list of endpoint function drivers in the system:

```
# ls /sys/bus/pci-epf/drivers
pci_epf_ntb  pci_epf_ntb
```

If PCI_ENDPOINT_CONFIGFS is enabled:

```
# ls /sys/kernel/config/pci_ep/functions
pci_epf_ntb  pci_epf_ntb
```

Creating pci-epf-ntb Device

PCI endpoint function device can be created using the configfs. To create pci-epf-ntb device, the following commands can be used:

```
# mount -t configfs none /sys/kernel/config
# cd /sys/kernel/config/pci_ep/
# mkdir functions/pci_epf_ntb/func1
```

The "mkdir func1" above creates the pci-epf-ntb function device that will be probed by pci_epf_ntb driver.

The PCI endpoint framework populates the directory with the following configurable fields:

```
# ls functions/pci_epf_ntb/func1
baseclass_code    deviceid          msi_interrupts   pci-epf-ntb.0
progif_code       secondary         subsys_id        vendorid
cache_line_size   interrupt_pin    msix_interrupts primary
revid            subclass_code    subsys_vendor_id
```

The PCI endpoint function driver populates these entries with default values when the device is bound to the driver. The pci-epf-ntb driver populates vendorid with 0xffff and interrupt_pin with 0x0001:

```
# cat functions/pci_epf_ntb/func1/vendorid  
0xffff  
# cat functions/pci_epf_ntb/func1/interrupt_pin  
0x0001
```

Configuring pci-epf-ntb Device

The user can configure the pci-epf-ntb device using its configfs entry. In order to change the vendorid and the deviceid, the following commands can be used:

```
# echo 0x104c > functions/pci_epf_ntb/func1/vendorid  
# echo 0xb00d > functions/pci_epf_ntb/func1/deviceid
```

The PCI endpoint framework also automatically creates a sub-directory in the function attribute directory. This sub-directory has the same name as the name of the function device and is populated with the following NTB specific attributes that can be configured by the user:

```
# ls functions/pci_epf_ntb/func1/pci_epf_ntb.0/  
db_count      mw1          mw2          mw3          mw4          num_mws  
spad_count
```

A sample configuration for NTB function is given below:

```
# echo 4 > functions/pci_ntb/func1/pci_epf_ntb.0/db_count  
# echo 128 > functions/pci_ntb/func1/pci_epf_ntb.0/spad_count  
# echo 2 > functions/pci_ntb/func1/pci_epf_ntb.0/num_mws  
# echo 0x100000 > functions/pci_ntb/func1/pci_epf_ntb.0/mw1  
# echo 0x100000 > functions/pci_ntb/func1/pci_epf_ntb.0/mw2
```

Binding pci-epf-ntb Device to EP Controller

NTB function device should be attached to two PCI endpoint controllers connected to the two hosts. Use the 'primary' and 'secondary' entries inside NTB function device to attach one PCI endpoint controller to primary interface and the other PCI endpoint controller to the secondary interface:

```
# ln -s controllers/2900000.pcie-ep/ functions/pci-epf-ntb/func1/primary  
# ln -s controllers/2910000.pcie-ep/ functions/pci-epf-ntb/func1/secondary
```

Once the above step is completed, both the PCI endpoint controllers are ready to establish a link with the host.

Start the Link

In order for the endpoint device to establish a link with the host, the `_start_` field should be populated with '1'. For NTB, both the PCI endpoint controllers should establish link with the host:

```
# echo 1 > controllers/2900000.pcie-ep/start
# echo 1 > controllers/2910000.pcie-ep/start
```

9.7.2 RootComplex Device

Ispci Output

Note that the devices listed here correspond to the values populated in "Creating pci-epf-ntb Device" section above:

```
# lspci
0000:00:00.0 PCI bridge: Texas Instruments Device b00d
0000:01:00.0 RAM memory: Texas Instruments Device b00d
```

Using ntb_hw_efp Device

The host side software follows the standard NTB software architecture in Linux. All the existing client side NTB utilities like NTB Transport Client and NTB Netdev, NTB Ping Pong Test Client and NTB Tool Test Client can be used with NTB function device.

For more information on NTB see Non-Transparent Bridge

9.8 PCI vNTB Function

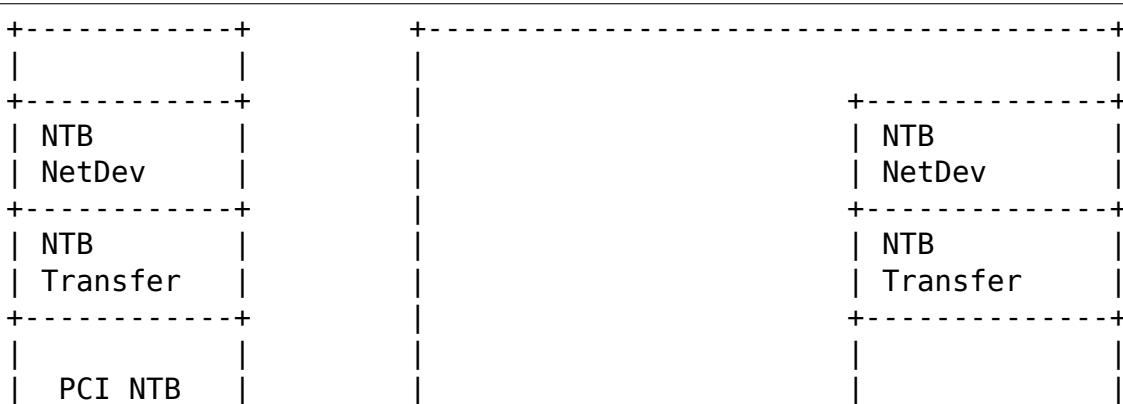
Author

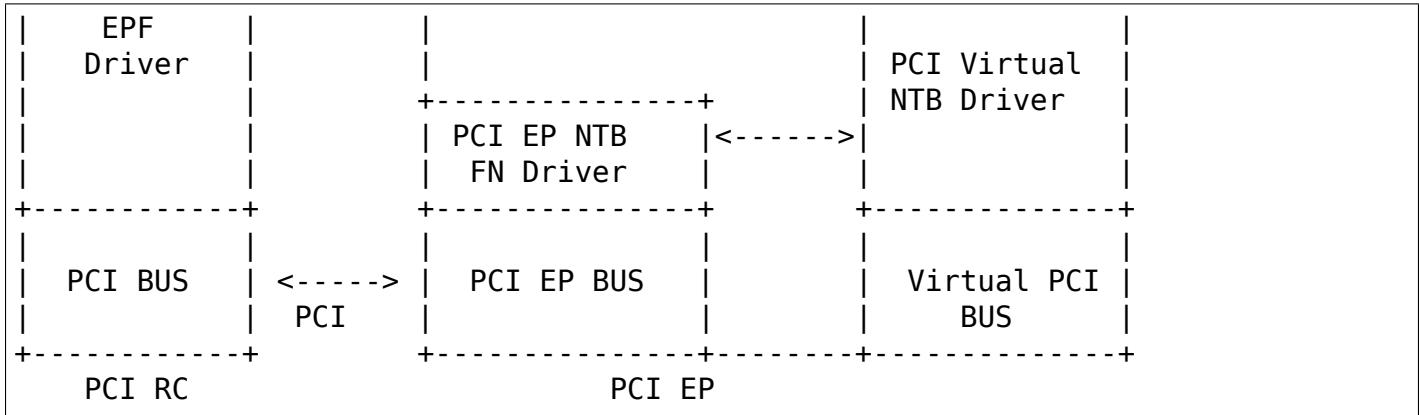
Frank Li <Frank.Li@nxp.com>

The difference between PCI NTB function and PCI vNTB function is

PCI NTB function need at two endpoint instances and connect HOST1 and HOST2.

PCI vNTB function only use one host and one endpoint(EP), use NTB connect EP and PCI host





9.8.1 Constructs used for Implementing vNTB

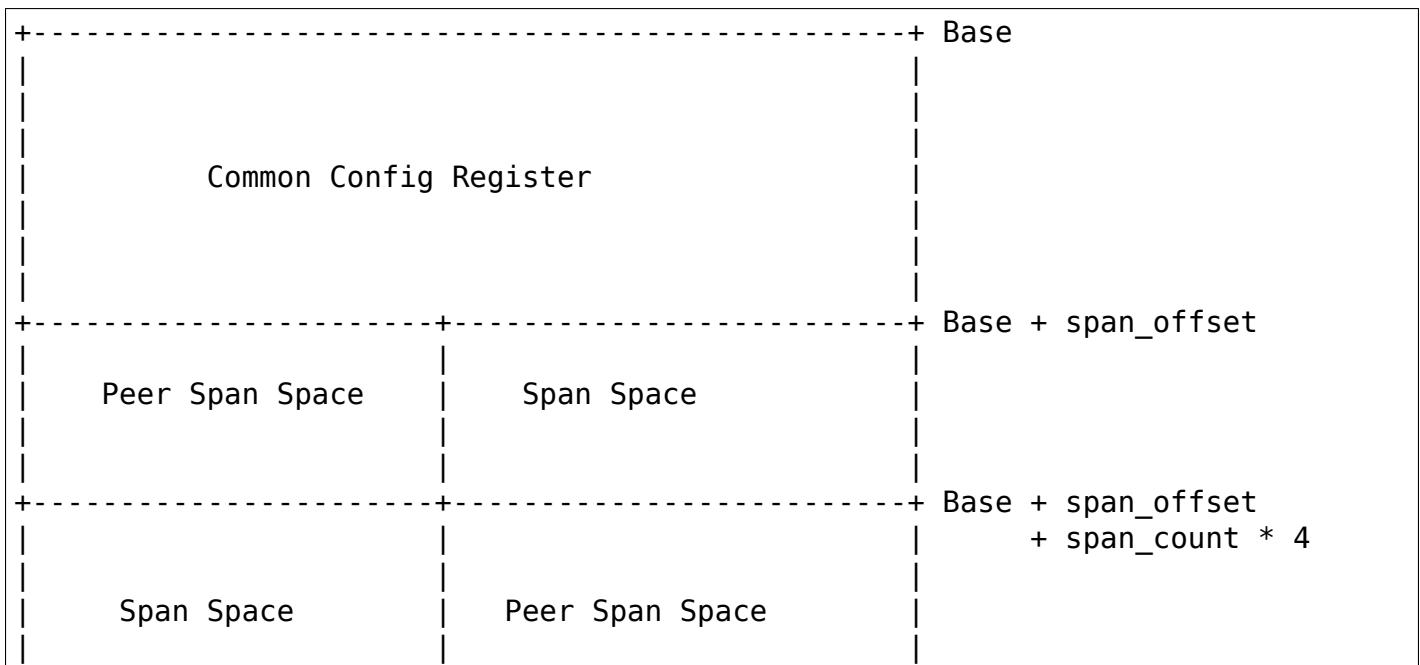
- 1) Config Region
- 2) Self Scratchpad Registers
- 3) Peer Scratchpad Registers
- 4) Doorbell (DB) Registers
- 5) Memory Window (MW)

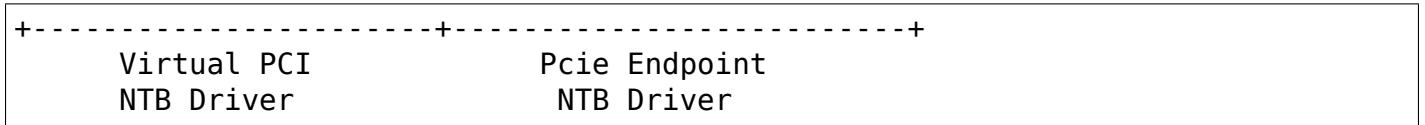
Config Region:

It is same as PCI NTB Function driver

Scratchpad Registers:

It is appended after Config region.





Doorbell Registers:

Doorbell Registers are used by the hosts to interrupt each other.

Memory Window:

Actual transfer of data between the two hosts will happen using the memory window.

9.8.2 Modeling Constructs:

32-bit BARs.

BAR NO	CONSTRUCTS USED
BAR0	Config Region
BAR1	Doorbell
BAR2	Memory Window 1
BAR3	Memory Window 2
BAR4	Memory Window 3
BAR5	Memory Window 4

64-bit BARs.

BAR NO	CONSTRUCTS USED
BAR0	Config Region + Scratchpad
BAR1	
BAR2	Doorbell
BAR3	
BAR4	Memory Window 1
BAR5	

9.9 PCI Non-Transparent Bridge (NTB) Endpoint Function (EPF) User Guide

Author

Frank Li <Frank.Li@nxp.com>

This document is a guide to help users use pci-epf-vntb function driver and ntb_hw_epf host driver for NTB functionality. The list of steps to be followed in the host side and EP side is given below. For the hardware configuration and internals of NTB using configurable endpoints see *PCI vNTB Function*

9.9.1 Endpoint Device

Endpoint Controller Devices

To find the list of endpoint controller devices in the system:

```
# ls /sys/class/pci_epc/  
5f010000.pcie_ep
```

If PCI_ENDPOINT_CONFIGFS is enabled:

```
# ls /sys/kernel/config/pci_ep/controllers  
5f010000.pcie_ep
```

Endpoint Function Drivers

To find the list of endpoint function drivers in the system:

```
# ls /sys/bus/pci-epf/drivers  
pci_epf_ntb  pci_epf_test  pci_epf_vntb
```

If PCI_ENDPOINT_CONFIGFS is enabled:

```
# ls /sys/kernel/config/pci_ep/functions  
pci_epf_ntb  pci_epf_test  pci_epf_vntb
```

Creating pci-epf-vntb Device

PCI endpoint function device can be created using the configfs. To create pci-epf-vntb device, the following commands can be used:

```
# mount -t configfs none /sys/kernel/config  
# cd /sys/kernel/config/pci_ep/  
# mkdir functions/pci_epf_vntb/func1
```

The "mkdir func1" above creates the pci-epf-ntb function device that will be probed by pci_epf_vntb driver.

The PCI endpoint framework populates the directory with the following configurable fields:

```
# ls functions/pci_epf_ntb/func1  
baseclass_code      deviceid          msi_interrupts    pci-epf-ntb.0  
progif_code        secondary         subsys_id       vendorid  
cache_line_size    interrupt_pin   msix_interrupts  primary  
revid              subclass_code   subsys_vendor_id
```

The PCI endpoint function driver populates these entries with default values when the device is bound to the driver. The pci-epf-vntb driver populates vendorid with 0xffff and interrupt_pin with 0x0001:

```
# cat functions/pci_epf_vntb/func1/vendorid
0xffff
# cat functions/pci_epf_vntb/func1/interrupt_pin
0x0001
```

Configuring pci-epf-vntb Device

The user can configure the pci-epf-vntb device using its configfs entry. In order to change the vendorid and the deviceid, the following commands can be used:

```
# echo 0x1957 > functions/pci_epf_vntb/func1/vendorid
# echo 0x0809 > functions/pci_epf_vntb/func1/deviceid
```

The PCI endpoint framework also automatically creates a sub-directory in the function attribute directory. This sub-directory has the same name as the name of the function device and is populated with the following NTB specific attributes that can be configured by the user:

```
# ls functions/pci_epf_vntb/func1/pci_epf_vntb.0/
db_count      mw1          mw2          mw3          mw4          num_mws
spad_count
```

A sample configuration for NTB function is given below:

```
# echo 4 > functions/pci_epf_vntb/func1/pci_epf_vntb.0/db_count
# echo 128 > functions/pci_epf_vntb/func1/pci_epf_vntb.0/spad_count
# echo 1 > functions/pci_epf_vntb/func1/pci_epf_vntb.0/num_mws
# echo 0x100000 > functions/pci_epf_vntb/func1/pci_epf_vntb.0/mw1
```

A sample configuration for virtual NTB driver for virtual PCI bus:

```
# echo 0x1957 > functions/pci_epf_vntb/func1/pci_epf_vntb.0/vntb_vid
# echo 0x080A > functions/pci_epf_vntb/func1/pci_epf_vntb.0/vntb_pid
# echo 0x10 > functions/pci_epf_vntb/func1/pci_epf_vntb.0/vbus_number
```

Binding pci-epf-ntb Device to EP Controller

NTB function device should be attached to PCI endpoint controllers connected to the host.

```
# ln -s controllers/5f010000.pcie_ep functions/pci-epf-ntb/func1/primary
```

Once the above step is completed, the PCI endpoint controllers are ready to establish a link with the host.

Start the Link

In order for the endpoint device to establish a link with the host, the `_start_` field should be populated with '1'. For NTB, both the PCI endpoint controllers should establish link with the host (imx8 don't need this steps):

```
# echo 1 > controllers/5f010000.pcie_ep/start
```

9.9.2 RootComplex Device

Ispci Output at Host side

Note that the devices listed here correspond to the values populated in "Creating pci-epf-ntb Device" section above:

```
# lspci  
00:00.0 PCI bridge: Freescale Semiconductor Inc Device 0000 (rev 01)  
01:00.0 RAM memory: Freescale Semiconductor Inc Device 0809
```

9.9.3 Endpoint Device / Virtual PCI bus

Ispci Output at EP Side / Virtual PCI bus

Note that the devices listed here correspond to the values populated in "Creating pci-epf-ntb Device" section above:

```
# lspci  
10:00.0 Unassigned class [ffff]: Dawicontrol Computersysteme GmbH Device 1234  
  ↳ (rev ff)
```

Using ntb_hw_efp Device

The host side software follows the standard NTB software architecture in Linux. All the existing client side NTB utilities like NTB Transport Client and NTB Netdev, NTB Ping Pong Test Client and NTB Tool Test Client can be used with NTB function device.

For more information on NTB see Non-Transparent Bridge

9.10 PCI Test Endpoint Function

name: Should be "pci_efp_test" to bind to the pci_efp_test driver.

Configurable Fields:

vendorid	should be 0x104c
deviceid	should be 0xb500 for DRA74x and 0xb501 for DRA72x
revid	don't care
progif_code	don't care
subclass_code	don't care
baseclass_code	should be 0xff
cache_line_size	don't care
subsys_vendor_id	don't care
subsys_id	don't care
interrupt_pin	Should be 1 - INTA, 2 - INTB, 3 - INTC, 4 -INTD
msi_interrupts	Should be 1 to 32 depending on the number of MSI interrupts to test
msix_interrupts	Should be 1 to 2048 depending on the number of MSI-X interrupts to test

9.11 PCI NTB Endpoint Function

- 1) Create a subdirectory to pci_epf_ntb directory in configs.

Standard EPF Configurable Fields:

vendorid	should be 0x104c
deviceid	should be 0xb00d for TI's J721E SoC
revid	don't care
progif_code	don't care
subclass_code	should be 0x00
baseclass_code	should be 0x5
cache_line_size	don't care
subsys_vendor_id	don't care
subsys_id	don't care
interrupt_pin	don't care
msi_interrupts	don't care
msix_interrupts	don't care

- 2) Create a subdirectory to directory created in 1

NTB EPF specific configurable fields:

db_count	Number of doorbells; default = 4
mw1	size of memory window1
mw2	size of memory window2
mw3	size of memory window3
mw4	size of memory window4
num_mws	Number of memory windows; max = 4
spad_count	Number of scratchpad registers; default = 64

BOOT INTERRUPTS

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10.1 Overview

On PCI Express, interrupts are represented with either MSI or inbound interrupt messages (Assert_INTx/Deassert_INTx). The integrated IO-APIC in a given Core IO converts the legacy interrupt messages from PCI Express to MSI interrupts. If the IO-APIC is disabled (via the mask bits in the IO-APIC table entries), the messages are routed to the legacy PCH. This in-band interrupt mechanism was traditionally necessary for systems that did not support the IO-APIC and for boot. Intel in the past has used the term "boot interrupts" to describe this mechanism. Further, the PCI Express protocol describes this in-band legacy wire-interrupt INTx mechanism for I/O devices to signal PCI-style level interrupts. The subsequent paragraphs describe problems with the Core IO handling of INTx message routing to the PCH and mitigation within BIOS and the OS.

10.2 Issue

When in-band legacy INTx messages are forwarded to the PCH, they in turn trigger a new interrupt for which the OS likely lacks a handler. When an interrupt goes unhandled over time, they are tracked by the Linux kernel as Spurious Interrupts. The IRQ will be disabled by the Linux kernel after it reaches a specific count with the error "nobody cared". This disabled IRQ now prevents valid usage by an existing interrupt which may happen to share the IRQ line:

```
irq 19: nobody cared (try booting with the "irqpoll" option)
CPU: 0 PID: 2988 Comm: irq/34-nipalk Tainted: 4.14.87-rt49-02410-g4a640ec-
dirty #1
Hardware name: National Instruments NI PXIE-8880/NI PXIE-8880, BIOS 2.1.5f1 01/
09/2020
Call Trace:

<IRQ>
? dump_stack+0x46/0x5e
? __report_bad_irq+0x2e/0xb0
? note_interrupt+0x242/0x290
? nNIKAL100_memoryRead16+0x8/0x10 [nikal]
```

```
? handle_irq_event_percpu+0x55/0x70
? handle_irq_event+0x4f/0x80
? handle_fasteoi_irq+0x81/0x180
? handle_irq+0x1c/0x30
? do_IRQ+0x41/0xd0
? common_interrupt+0x84/0x84
</IRQ>

handlers:
irq_default_primary_handler threaded usb_hcd_irq
Disabling IRQ #19
```

10.3 Conditions

The use of threaded interrupts is the most likely condition to trigger this problem today. Threaded interrupts may not be re-enabled after the IRQ handler wakes. These "one shot" conditions mean that the threaded interrupt needs to keep the interrupt line masked until the threaded handler has run. Especially when dealing with high data rate interrupts, the thread needs to run to completion; otherwise some handlers will end up in stack overflows since the interrupt of the issuing device is still active.

10.4 Affected Chipsets

The legacy interrupt forwarding mechanism exists today in a number of devices including but not limited to chipsets from AMD/ATI, Broadcom, and Intel. Changes made through the mitigations below have been applied to drivers/pci/quirks.c

Starting with ICX there are no longer any IO-APICs in the Core IO's devices. IO-APIC is only in the PCH. Devices connected to the Core IO's PCIe Root Ports will use native MSI/MSI-X mechanisms.

10.5 Mitigations

The mitigations take the form of PCI quirks. The preference has been to first identify and make use of a means to disable the routing to the PCH. In such a case a quirk to disable boot interrupt generation can be added.¹

Intel® 6300ESB I/O Controller Hub

Alternate Base Address Register:

BIE: Boot Interrupt Enable

0	Boot interrupt is enabled.
1	Boot interrupt is disabled.

Intel® Sandy Bridge through Sky Lake based Xeon servers:

¹ <https://lore.kernel.org/r/12131949181903-git-send-email-sassmann@suse.de/>

Coherent Interface Protocol Interrupt Control

dis_intx_route2pch/dis_intx_route2ich/dis_intx_route2dmi2:

When this bit is set. Local INTx messages received from the Intel® Quick Data DMA/PCI Express ports are not routed to legacy PCH - they are either converted into MSI via the integrated IO-APIC (if the IO-APIC mask bit is clear in the appropriate entries) or cause no further action (when mask bit is set)

In the absence of a way to directly disable the routing, another approach has been to make use of PCI Interrupt pin to INTx routing tables for purposes of redirecting the interrupt handler to the rerouted interrupt line by default. Therefore, on chipsets where this INTx routing cannot be disabled, the Linux kernel will reroute the valid interrupt to its legacy interrupt. This redirection of the handler will prevent the occurrence of the spurious interrupt detection which would ordinarily disable the IRQ line due to excessive unhandled counts.²

The config option X86_REROUTE_FOR_BROKEN_BOOT_IRQS exists to enable (or disable) the redirection of the interrupt handler to the PCH interrupt line. The option can be overridden by either pci=ioapicreroute or pci=noioapicreroute.³

10.6 More Documentation

There is an overview of the legacy interrupt handling in several datasheets (6300ESB and 6700PXH below). While largely the same, it provides insight into the evolution of its handling with chipsets.

10.6.1 Example of disabling of the boot interrupt

- Intel® 6300ESB I/O Controller Hub (Document # 300641-004US) 5.7.3 Boot Interrupt <https://www.intel.com/content/dam/doc/datasheet/6300esb-io-controller-hub-datasheet.pdf>
- Intel® Xeon® Processor E5-1600/2400/2600/4600 v3 Product Families Datasheet - Volume 2: Registers (Document # 330784-003) 6.6.41 cipintrc Coherent Interface Protocol Interrupt Control <https://www.intel.com/content/dam/www/public/us/en/documents/datasheets/xeon-e5-v3-datasheet-vol-2.pdf>

10.6.2 Example of handler rerouting

- Intel® 6700PXH 64-bit PCI Hub (Document # 302628) 2.15.2 PCI Express Legacy INTx Support and Boot Interrupt <https://www.intel.com/content/dam/doc/datasheet/6700pxh-64-bit-pci-hub-datasheet.pdf>

If you have any legacy PCI interrupt questions that aren't answered, email me.

Cheers,

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² <https://lore.kernel.org/r/12131949182094-git-send-email-sassmann@suse.de/>

³ <https://lore.kernel.org/r/487C8EA7.6020205@suse.de/>

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