Static Detection of Unsafe DMA Accesses in Device Drivers

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Jia-Ju Bai[1], Tuo Li[1], Kangjie Lu[2], Shi-Min Hu[1]

[1]Tsinghua University, [2]University of Minnesota

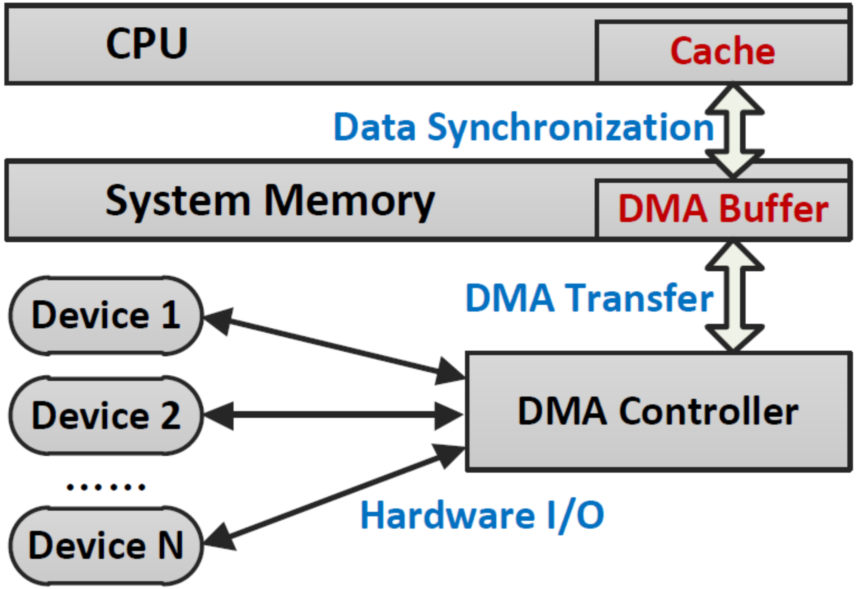
https://baijiaju.github.io/

Tsinghua University

University of Minnesota Driven to Discover®

Background

- DMA is widely used in modern device drivers
  - Direct data transfer between hardware registers and system memory
  - Perform data transfer without CPU involvement



DMA access

- Basic steps
  - S1: Create a DMA buffer
  - S2: Perform a DMA access like a regular variable access

    Read a DMA buffer: data = dma_buf->data;

    Write a DMA buffer: dma_buf->data = data;
  - S3: Delete a DMA buffer

DMA type

- Streaming DMA buffer
  - It is asynchronously available to both the CPU and hardware device
  - The driver needs to explicitly synchronize the data between hardware registers and CPU cache
  - Each DMA access is relatively cheap
- Coherent DMA buffer
  - It is simultaneously available to both the CPU and hardware device
  - The driver does not need to explicitly synchronize the data between hardware registers and CPU cache
  - Each DMA access is relatively expensive

Security risks of DMA access

- Streaming DMA access
  - After a streaming DMA buffer is created, the driver should not access the content of this buffer, until this buffer is unmapped
  - The driver is allowed to access buffer content during synchronization with hardware registers and CPU cache
- Security risks of violations
  - ***Inconsistent DMA access***
  - Data inconsistency between hardware registers and CPU cache

Example

- Inconsistent DMA access in the Linux *rtl8192ce* driver
  - Introduced in Linux 4.4 (released in Jan. 2016)
  - Fixed in Oct. 2020 by us

FILE: linux-5.6/drivers/net/wireless/realtek/rtlwifi/rtl8192ce/trx.c

```
522. void rtl92ce_tx_fill_cmddesc(...) {
          ......
          // Streaming DMA mapping
531.      dma_addr_t mapping = pci_map_single(..., skb->data, ...);
          ......
535.      struct ieee80211_hdr *hdr = (struct ieee80211_hdr *)(skb->data);
536       fc = hdr->frame_control;  // Inconsistent DMA access!
          ......
584. }
```

Security risks of DMA access

- Coherent DMA access
  - The hardware device can be untrusted, and thus can write bad data into coherent DMA buffers, which are used by the driver
  - The driver should perform correct validation of the data from DMA buffers before using the data
- Security risks of violations
  - ***Unchecked DMA access***
  - Security bugs, such as buffer overflow and invalid-pointer access

Example

- Unchecked DMA access in the Linux *vmxnet3* driver
  - Introduced in Linux 3.16 (released in Aug. 2014)
  - Fixed in Jun. 2020 by us

FILE: linux-5.6/drivers/net/vmxnet3/vmxnet3_ethtool.c

```
693. static int vmxnet3_get_rss(...) {
        ......
696.    struct UPT1_RSSConf *rssConf = adapter->rss_conf;
697.    unsigned int n = rssConf->indTableSize;
        ......
704.    while (n--)
705.        p[n] = rssConf->indTable[n];  // Possible buffer overflow
706.    return 0;
707. }
```

FILE: linux-5.6/drivers/net/vmxnet3/vmxnet3_drv.c

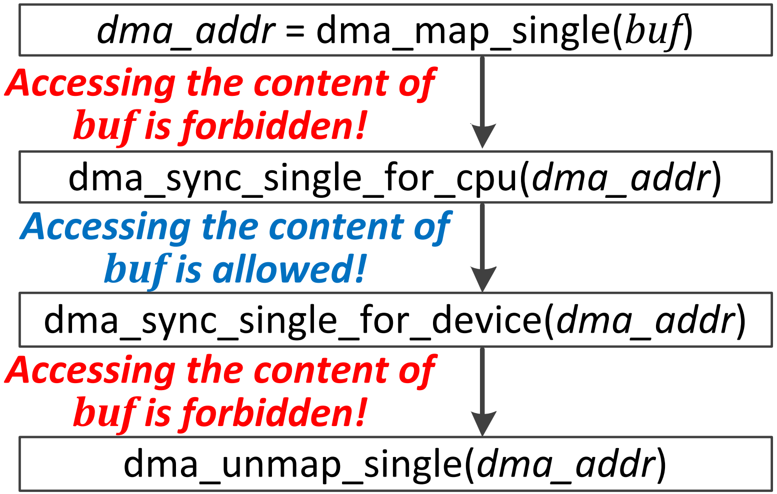
```
3240. static int vmxnet3_probe_device(...) {
          ......
          // Coherent DMA allocation
3373.     adapter->rss_conf = dma_alloc_coherent(...);
          ......
3531. }
```

FILE: linux-5.6/drivers/net/vmxnet3/upt1_defs.h

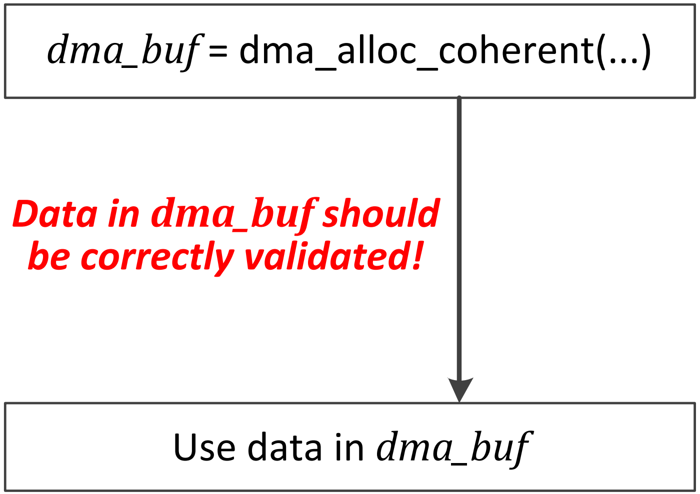
```
80. struct UPT1_RSSConf {
81.     u16 hashType;
        ......
86.     u8 indTable[UPT1_RSS_MAX_IND_TABLE_SIZE]; // Bound is 128
87. }
```

Unsafe DMA access

- Basic rules



Streaming DMA access



Coherent DMA access

Challenges of detecting unsafe DMA access

- ***C1: Identifying DMA access***
  - Each DMA access is implemented as a regular variable access, without calling specific interface functions
  - DMA creation and DMA access often have no explicit execution order from static code observation, namely in a *broken control flow*
- ***C2: Checking the safety of DMA access***
  - Accuracy and efficiency of analyzing large OS code
- ***C3: Dropping false positives***
  - Validating code-path feasibility is difficult and expensive

Key techniques

- ***C1: Identifying DMA access***
  - ***Field-based alias analysis*** to effectively identify DMA access
- ***C2: Checking the safety of DMA accesses***
  - ***Flow-sensitive and pattern-based analysis*** to accurately and efficiently check the safety of DMA access
- ***C3: Dropping false positives***
  - ***Efficient code-path validation method*** to drop false positives and reduce the overhead of using a SMT solver

DMA-access identification

- S1: Handling DMA-buffer creation
  - Identify DMA-creation function calls
  - Collect the information about their return variables, including variable names, data structure types and fields
- S2: Identifying DMA access
  - Check each variable access in the driver
  - If variable name or data structure information matches the collected information, the access is identified to be a DMA access
- Alias analysis is useful to handling variable assignments
  - Intra-procedural, flow-insensitive and Andersen-style alias analysis

DMA-access safety checking

- Checking streaming DMA access
  - Four patterns about DMA operations
  - Forward and backward flow-sensitive analysis

dma_addr = dma_map_single(*buf*) ***// Start***
↓ ***Forward flow-sensitive analysis***
Read or write the content of *buf* ***// Report!***

Pattern 1

dma_sync_single_for_device(*dma_addr*) ***// Start***
↓ ***Forward flow-sensitive analysis***
Read or write the content of *buf* ***// Report!***

Pattern 2

Read or write the content of *buf* ***// Report!***
↑ ***Backward flow-sensitive analysis***
dma_unmap_single(*dma_addr*) ***// Start***

Pattern 3

Read or write the content of *buf* ***// Report!***
↑ ***Backward flow-sensitive analysis***
dma_sync_single_for_cpu(*dma_addr*) ***// Start***

Pattern 4

DMA-access safety checking

- Checking coherent DMA access
  - Flow-sensitive taint analysis to identify DMA-affected operations
  - Three patterns about security problems

```
FILE: linux-5.6/drivers/net/wireless/intel/iwlwifi/pcie/rx.c
1693. static u32 iwl_pcie_int_cause_ict(...) {
        ......
1714.   do {
          ......
1722.     read = trans_pcie->ict_tbl[...];
          ......
1725.   } while (read);  // Possible bug
        ......
1743. }
- - - - - - - - - - - - - - - - - - - - - - - - - - - - -
2054. int iwl_pcie_alloc_ict(...) {
        ......
        // Coherent DMA allocation
2058.   trans_pcie->ict_tbl = dma_alloc_coherent(...);
        ......
2071. }
```

Pattern 1: Infinite loop polling

```
FILE: linux-5.6/drivers/net/wireless/intel/ipw2x00/ipw2100.c
2661. static void __ipw2100_rx_process(...) {
        ......
        // MASK is 0x0f
2701.   frame_type = sq->drv[i].status_fields & MASK;
        ......
        // Possible bug
2710.   IPW_DEBUG_RX(..., frame_types[frame_type], ...)
        ......
2765. }
- - - - - - - - - - - - - - - - - - - - - - - - - - - - -
4318. static int status_queue_allocate(...) {
        ......
        // Coherent DMA allocation
4325.   q->drv = pci_zalloc_consistent(...);
        ......
4334. }
```

Pattern 2: Buffer overflow

```
FILE: linux-5.6/drivers/net/ethernet/socionext/netsec.c
 931. static int netsec_process_rx(...) {
        ......
 948.   struct netsec_de *de = dring->vaddr + ...;
        ......
 971.   pkt_len = de->buf_len_info >> 16;
        ......
        // Possible bug, as xdp.data is a pointer
1003.   xdp.data_end = xdp.data + pkt_len;
        ......
1059. }
- - - - - - - - - - - - - - - - - - - - - - - - - - - - -
1241. static int netsec_alloc_dring(...) {
        // Coherent DMA allocation
1245.   dring->vaddr = dma_alloc_coherent(...);
        ......
1259. }
```

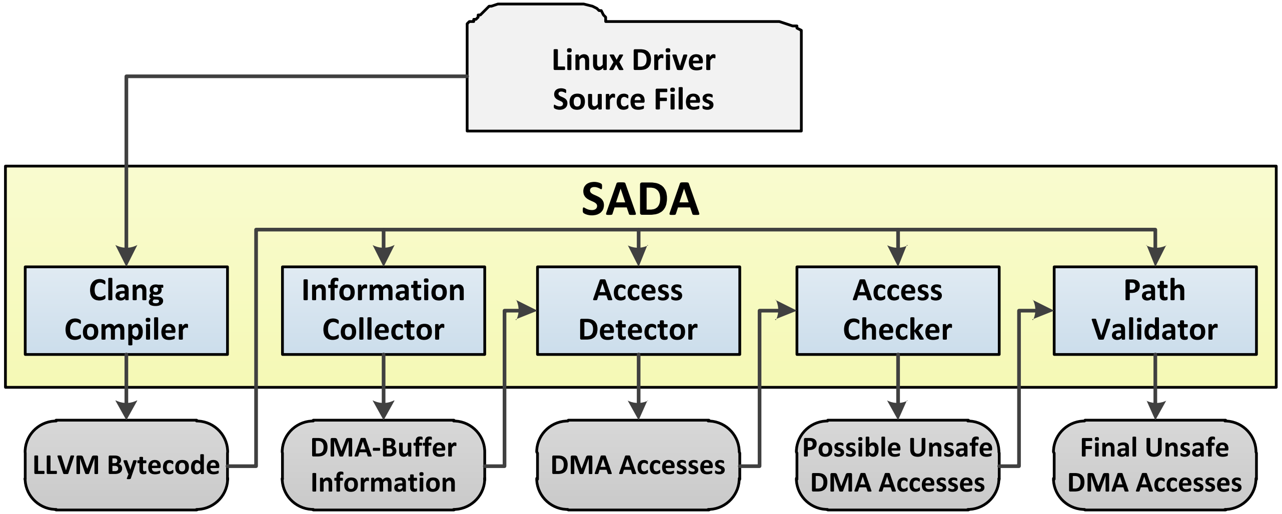
Pattern 3: Invalid pointer access

Code-Path Validation

- S1: Getting path constraints
  - Translate each instruction in the code path to an Z3 constraint
  - ***Example:*** "*a = b + c*" -> "*a == b + c*"
- S2: Adding additional constraints
  - Identify and add constraints that can trigger security bugs
  - ***Example:*** For buffer overflow, add "*frame > MAX_SIZE*" when *frame* is an index to access an array whose bound is *MAX_SIZE*
- S3: Solving all constraints
  - If the constraints cannot be satisfied, the possible unsafe DMA access is identified as a false positive and is dropped

Approach

- **SADA** (<u>S</u>tatic <u>A</u>nalysis of <u>D</u>MA <u>A</u>ccess)
  - Integrate the three key techniques
  - Statically detect unsafe DMA access in device drivers
  - LLVM-based static analysis



Evaluation

- Driver code in Linux 5.6
  - Use a regular PC with eight CPUs and 16GB memory
  - Use Clang-9.0
  - Make *allyesconfig* of x86-64
  - Check the kernel directories *drivers/* and *sound/*

Evaluation

- Detection of unsafe DMA accesses

Description		Linux 5.6
Code handling	Source files (.c)	14.6K
	Source code lines	8.8M
DMA-access identification	Encountered DMA-buffer creation	2,781
	DMA buffers in data structure fields	2,074
	Identified DMA accesses	28,732
DMA-access checking	Unsafe DMA accesses (real / all)	284 / 321
	Inconsistent DMA accesses (real / all)	123 / 131
	Unchecked DMA accesses (real / all)	161 / 190
Time usage	DMA-access identification	62m
	DMA-access checking	208m
	Total time	270m

Evaluation

- 123 inconsistent DMA accesses
  - Direct access after DMA creation: 108
  - Incorrect DMA synchronization: 15
- 161 unchecked DMA accesses
  - Buffer overflow: 121
  - Invalid-pointer access: 36
  - Infinite loop polling: 4
- 105 of the 284 real unsafe DMA accesses have been confirmed by driver developers

Limitations

- False positives
  - The current alias analyses is simple and not accurate enough
  - The path validation can make mistakes in complex cases
  - ……
- False negatives
  - Lack the analysis of function-pointer calls
  - Neglect other patterns of unsafe DMA accesses
  - ……

Conclusion

- DMA is popular in modern device drivers but can introduce security risks in practice
- SADA: static detection of unsafe DMA accesses
  - ***Field-based alias analysis*** to effectively identify DMA accesses
  - ***Flow-sensitive and pattern-based analysis*** to accurately and efficiently check the safety of DMA accesses
  - ***Efficient code-path validation method*** to drop false positives and reduce the overhead of using SMT solvers
- Find 284 real unsafe DMA accesses in Linux 5.6

Thanks for listening!

Jia-Ju Bai

E-mail: baijiaju@tsinghua.edu.cn

https://baijiaju.github.io/