Automatic Verification of Message-Based Device Drivers

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We develop a practical solution to the problem of automatic verification of the interface between device drivers and the OS. Our solution relies on a combination of improved driver architecture and verification tools. It supports drivers written in C and can be implemented in any existing OS, which sets it apart from previous proposals for verification-friendly drivers. Our Linux-based evaluation shows that this methodology amplifies the power of existing verification tools in detecting driver bugs, making it possible to verify properties beyond the reach of traditional techniques.

1 Introduction

Faulty device drivers are a major source of operating system (OS) failures [14, 7]. Recent studies of Windows and Linux drivers show that over a third of driver bugs result from the complex interface between driver and OS [21, 3]. The OS defines numerous rules on the ordering and arguments of driver invocations, rules that often are neither well documented nor are stable across OS releases. Worse, the OS can invoke driver functions from multiple concurrent threads, and so driver developers must implement complex synchronisation logic to avoid races and deadlocks.

In addition to causing numerous programming errors, these problems complicate formal analysis of device driver code. While automatic verification has proved useful in detecting OS interface violations in device drivers, driver verification tools remain limited in the complexity of properties that can be verified efficiently [3, 9, 8, 16, 11].

One way to address the problem is through an improved device driver architecture that simplifies driver development and makes them more amenable to automatic verification [12, 4]. In this architecture each driver has its own thread and communicates with the OS using message passing, which makes the driver control flow and its interactions with the OS easier to understand and analyse. We refer to such drivers as *active drivers*, in contrast to conventional, *passive*, drivers that are structured as collections of entry points invoked by OS threads.

Previous implementations of active drivers in Singularity [12] and RMoX [4] OSs rely on OS and language support for improved verifiability. As such, they do not help address the driver reliability problem in mainstream operating systems written in C.

In this paper we show that the benefits of active drivers can be achieved while writing drivers in C for a conventional OS. To this end, we present an implementation of an active driver framework for Linux along with a new verification method that enables efficient, automatic checking of active driver protocols. Our method leverages existing verification tools for C, extended with several novel optimisations geared towards making active driver verification tractable. Like other existing automatic verification techniques, the method is not complete—it helps to find bugs, but does not guarantee their absence.

Through experiments involving verification of several complex drivers for Linux, we demonstrate that our driver design and verification methodology amplifies the power of verification tools in finding

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driver bugs. In particular, many properties that are hard or impossible to verify in conventional drivers can be easily checked on active drivers.

In this paper we focus on verification of active device drivers. A detailed account of the design and implementation of the active driver framework for Linux and its peformance evaluation can be found in the accompanying technical report [2].

The rest of the paper is structured as follows. Section 2 introduces the active driver architecture. Section 3 presents our visual formalism for specifying active driver protocols. Section 4 describes our verification methodology. Section 5 outlines the design and implementation of the active driver framework for Linux. Section 6 presents experimental results. Section 7 surveys related work on device driver verification. Section 8 concludes the paper.

2 Passive vs active drivers

In this section we discuss the shortcomings of the conventional driver architecture and show how active drivers address these shortcomings.

Passive drivers The passive driver architecture supported by all mainstream OSs suffers from two problems that complicate verification of the driver-OS interface: *stack ripping* and *concurrency*.

A passive device driver comprises a collection of entry points invoked by the OS. When writing the driver, the programmer makes assumptions about possible orders in which its entry points are going to be activated; however these assumptions remain implicit in the implementation. As a result, the control flow of the driver is scattered across multiple entry points and cannot be reconstructed from its source code. This phenomenon is known as stack ripping [1].

To complicate things further, the OS can invoke driver entry points from multiple concurrent threads, forcing driver developers to implement intricate synchronisation logic to avoid races and deadlocks. Multithreading further complicates automatic verification of device drivers, as thread interleaving leads to dramatic state explosion.

Previous research [21] has shown that the vast majority of device drivers do not get any performance benefits from multithreading. The performance of most drivers is bound by I/O bandwidth rather than CPU speed, therefore they do not require true multiprocessor parallelism. Device drivers are multithreaded simply by virtue of executing within the multithreaded kernel environment and not because they require multithreading for performance or functionality.

Active drivers In contrast to passive drivers, an active driver runs in the context of its own thread. Communication between the driver and the OS occurs via message passing. The OS sends I/O requests and interrupt notifications to the driver using messages. The driver notifies the OS about completed requests via reply messages.

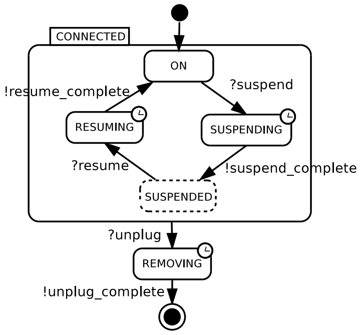
In an active device driver, the order in which the driver handles and responds to OS requests is defined explicitly in its source code and can be readily analysed automatically. Since the driver handles I/O requests sequentially, such analysis can be performed without running into state explosion due to thread interleaving.

We present our instantiation of the active driver architecture for Linux. Our design is based on the Dingo active driver framework [21], improving upon it in two ways. First, Dingo's message passing primitives are implemented as C language extensions. In contrast, our framework supports drivers in pure C. Second, Dingo does not support automatic driver protocol verification.

In our framework, the driver-OS interface consists of a set of *mailboxes*, where each mailbox is used for a particular type of message. The driver exchanges messages with the OS via `EMIT` and `AWAIT`

```
1 mb=AWAIT(suspend,unplug,..);
2 if (mb==suspend) {
3   dev_suspend();
4   EMIT(suspend_complete,msg);
5   //Bug! Uncomment to fix
6   mb=AWAIT(resume/*,unplug*/);
7   ...
8 } else if (mb==unplug) {
9   ...
10 }
```

(a) Faulty code



(b) Protocol

Figure 1: Fragment of active driver code and the matching protocol specification.

primitives, that operate on messages and mailboxes. The `EMIT` function takes a pointer to a mailbox, a message structure, and a list of message arguments. It places the message in the mailbox and returns control to the caller without blocking. The `AWAIT` function takes references to one or more mailboxes and blocks until a message arrives in one of them. It returns a reference to the mailbox containing the message. A mailbox can queue multiple messages. `AWAIT` always dequeues the first message in the mailbox. This message is accessible via a pointer in the returned mailbox.

Figure 1(a) shows a fragment of an active driver. In line 1 the driver waits on `suspend` and `unplug` mailboxes. After receiving a suspend request (checked by the condition at line 2) the driver suspends the device (line 3) and notifies the OS about completion of the request by sending a message to the `suspend_complete` mailbox (line 4). It then waits for a `resume` request at line 7. As can be seen from this example, requests that the driver accepts in each state are explicitly listed in the driver source code, which simplifies the analysis of driver behaviour and in particular its interaction with the OS.

3 Specifying driver protocols

This section presents our visual formalism for specifying active driver protocols. The formalism is similar to protocol state machines of Dingo [21] and Singularity [12], extended with additional means to capture liveness and fairness constraints, which enable the detection of additional types of driver bugs.

The active driver framework associates a protocol with each driver interface. The protocol specifies legal sequences of messages exchanged by the driver and the OS. Protocols are defined by the driver framework designer and are generic in the sense that every driver that implements the given interface must comply with the associated protocol. In the case when the active driver framework is implemented within an existing OS, the framework includes wrapper components that perform the translation between the native function-based interface and message-based active driver protocols.

We specify driver protocols using deterministic finite state machines (FSMs). The protocol state machine conceptually runs in parallel with the driver: whenever the driver sends or receives a message that belongs to the given protocol, this triggers a matching state transition in the protocol state machine. Figure 1(b) shows a state machine for the protocol used by the example driver, describing the handling of power management and hot unplug requests. Each protocol state transition is labelled with the name of the mailbox through which the driver sends ('!') or receives ('?') a message. We represent complex protocol state machines compactly using Statecharts [15], which organise states into a hierarchy so that several primitive states can be clustered into a super-state.

In some protocol states the OS is waiting for the driver to complete a request. The driver cannot remain in such a state indefinitely, but must eventually leave the state by sending a response message to the OS. Such states are called *timed* states and are labelled with the clock symbol in Figure 1(b).

In order to ensure that the driver does not deadlock in an `AWAIT` statement, the developer must rely on an additional assumption that if the driver waits for all incoming OS messages enabled in the current state, then one of them will eventually arrive. This is a form of *weak fairness* constraint [18] on the OS behaviour, which means that if some event (in this case, arrival of a message) is continuously enabled, it will finally occur. Not all protocol states have the weak fairness property. In the protocol state machine, we show fair states with dashed border. For example, the `SUSPENDED` state in Figure 1b is fair, which guarantees that at least one of `resume` and `unplug` messages will eventually arrive in this state.

A protocol-compliant device driver must obey the following 5 rules.

Rule 1. *(EMIT) The driver is allowed to emit a message to a mailbox iff this message triggers a valid state transition in the protocol state machine.*

Rule 2. *(AWAIT1) When in a state where there is an enabled incoming message, the driver must eventually issue an `AWAIT` on the corresponding mailbox or transition into a state where this message is not enabled.*

Rule 3. *(AWAIT2) All `AWAIT` operations eventually terminate. Equivalently, whenever the driver performs an `AWAIT` operation, at least one of its protocols must be in a fair state and the `AWAIT` must wait for all enabled messages of this protocol.*

Rule 4. *(Timed) The driver must not remain in a timed state forever.*

Rule 5. *(Termination) When the main driver function returns, the protocol state machine must be in a final state. Note that this rule does not require that every driver run terminates, merely that if it does terminate then all protocols must be in their final states.*

Rules 1, 3 and 5 describe *safety* properties, whose violation can be demonstrated by a finite execution trace. Rules 2 and 4 are *liveness* rules, for which counterexamples are infinite runs.

Going back to the example in Figure 1, we can see that the `AWAIT` statement in line 6 violates Rule 3. This line corresponds to the `SUSPENDED` state of the protocol, where the driver can receive `unplug` and `resume` messages. By waiting for only one of these messages, the driver can potentially deadlock.

4 Verifying driver protocols

The goal of driver protocol verification is to check whether the driver meets all safety and liveness requirements assuming fair OS behaviour. We use two tools to this end: SatAbs [8], geared towards safety analysis, and Goanna [13], geared towards liveness analysis. These tools provide complementary capabilities that, when combined, enable full verification of many driver protocols. We use SatAbs to check safety rules 1, 3, and 5 and Goanna to check liveness rules 2 and 4. This combination works well in practice, yielding a low overall false positive rate. Our methodology is compatible with other similar tools. We use SatAbs and Goanna because our team is familiar with their internals and has the expertise required to implement novel performance optimisations for these tools.

4.1 Checking safety

SatAbs is an abstraction-refinement based model checker for C and C++ for checking *safety* properties. It is designed to perform best when checking control-flow dominated properties with a small number of data dependencies. Active driver protocol-compliance safety checks fall into this category.

Given a program to verify, SATABS iteratively computes and verifies its finite-state abstraction with respect to a set of predicates over program variables. At each iteration it either terminates (by discovering a bug or proving that the program is correct) or generates a spurious counterexample. In the latter case, the counterexample is analysed by the tool to discover new predicates, used to construct a refined program abstraction. Abstraction and refinement are both fully automatic.

SATABS verifies program properties expressed as source code assertions. We encode rules 1 and 3 as assertions embedded in modified versions of `AWAIT` and `EMIT` functions. These functions keep track of the protocol state using a global state variable. The `AWAIT` function simulates the receiving of a message by randomly selecting one of incoming mailboxes enabled in the current state and updating the state variable based on the current state and the message selected. Similarly, the `EMIT` function updates the state variable based on the current state and the message being sent. It contains an assertion that triggers an error when the driver is trying to send a message that is not allowed in the current state. To verify rule 5, we append to the driver's main function a check to ensure that, if the driver does terminate, the protocol state machine is in a final state.

Our preliminary experiments show that straightforward application of SATABS to active drivers results in very long verification times. This is in part due to the complexity of driver protocols being verified and in part because predicate selection heuristics implemented in SATABS introduce large numbers of unnecessary predicates, leading to overly complex abstractions. The problem is not unique to SATABS. Our preliminary experiments with SLAM [3], another state-of-the-art abstraction-refinement tool, produced similar results. We describe several novel strategies that exploit the properties of active drivers to make their safety verification feasible. We believe that these techniques will also be useful in other software protocol verification tasks.

Protocol decomposition The abstraction-refinement technique is highly sensitive to the size of the property being checked. Complex properties require many predicates. Since verification time grows exponentially with the number of predicates, it is beneficial to decompose complex properties into simple ones that can be verified independenly.

We decompose each driver protocol state machine into a set of much simpler subprotocols as a preprocessing step. The decomposition is constructed in such a way that the driver satisfies safety constraints of the original protocol if and only if it does so for each protocol in the decomposition. The following proposition (stated informally) gives a sufficient condition for correctness of decomposition.

Proposition 1. *Consider a protocol P and its decomposition into protocols $P_1, \ldots, P_n$. If the following conditions hold then a driver satisfies P if and only if it satisfies each of $P_1, \ldots, P_n$:*

1. *The regular language generated by the protocol state machine of P is equivalent to the intersection of languages generated by $P_1, \ldots, P_n$.*
2. *There exists a bijection between fair states of P and the union of fair states of $P_1, \ldots, P_n$, such that for each fair state s of P and the corresponding fair state s' of P_i, the set of incoming messages enabled in s is equal to the set of incoming messages in s'.*

Figure 2 shows one possible decomposition of the protocol in Figure 1(b). Every subprotocol in the decomposition captures a simple rule related to a single type of message, shown in bold italics in the diagram. For instance, the third protocol from the left describes the occurrence of the `suspend` message: `suspend` can arrive in the initial state, is reenabled by the `resume_complete` message, and is permanently disabled by the `unplug` message. Messages that do not participate in the subprotocol are allowed in any state (as they are constrained by separate subprotocols) and are omitted in the diagram.

In our experience, even complex driver protocols allow decomposition into simple subprotocols with no more than four states and only a few transitions. Verifying each subprotocol requires a small subset of predicates involved in checking the monolithic protocol, leading to exponentially faster verification.

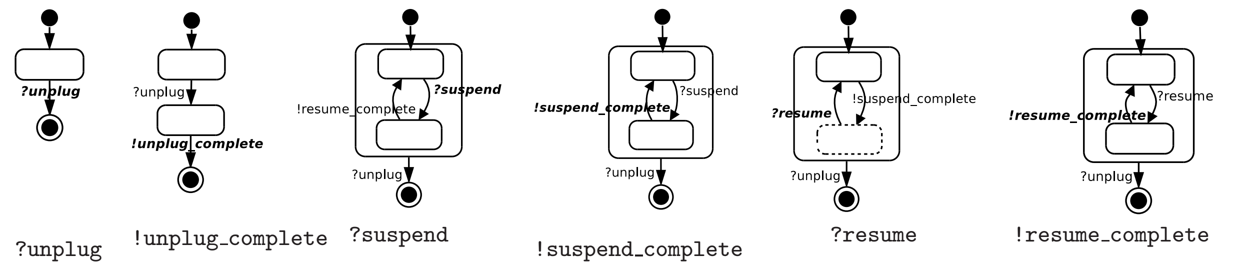


Figure 2: Decomposition of the protocol in Figure 1(b).

Correctness of a decomposition can be automatically checked based on Proposition 1. Furthermore, we found construction of protocol decompositions to be a largely mechanical task. As part of future work on the project we will investigate approaches to automating this task.

Automatically provide key predicates One way to speed-up the abstraction-refinement algorithm is to seed it with a small set of key predicates that avoid large families of spurious counterexamples. Guessing such key predicates *in general* is extremely difficult. In case of active driver verification, an important class of key predicates can be provided to SatAbs automatically.

As mentioned above, when checking a driver protocol, we introduce a global variable that keeps track of protocol state. During verification, SatAbs eventually discovers predicates over this variable of the form `(state==1)`, `(state==2)`, ..., one for each state of the protocol. These predicates are important to establishing the correspondence between the driver control flow and the protocol state machine. We therefore provide these predicates to SatAbs on startup, which accelerates verification significantly.

Control-flow transformations We found that it often takes SatAbs many iterations to correlate dependent program branches. This problem frequently occurs in active drivers when the driver `AWAIT`s on multiple mailboxes and then checks the returned value (e.g., line 2 in Figure 1(a)). If the driver executes the same comparison later in the execution, then both checks must produce the same outcome. SatAbs does not know about this correlation initially, leading to a spurious counterexample trace that takes inconsistent branches, potentially leading to spurious counteraexample traces. These counterexamples can be refuted using predicate $p \leftrightarrow (mb == suspend)$. In practice, however, SatAbs may introduce many predicates that only refute a subset of these counterexamples before discovering p, which allows refuting all of them.

To remedy the problem, we have implemented a novel control-flow graph transformation that uses static analysis to identify correlated branches, and merges them. The analysis identifies, through inspecting the use of the `AWAIT` function, where to apply the transformation. Then infeasible paths through each candidate region are identified by generating Boolean satisfiability queries which are discharged to a SAT solver. The CFG region is then rewritten to eliminate infeasible paths. The effect of the rewriting on the CFG is shown in Figure 3.

This technique effectively avoids the expensive search for additional predicates using much cheaper static program analysis. In our experiments, SatAbs performs orders of magnitude more effectively over the new program structure, being able to quickly infer key predicates that could previously only be inferred after many abstraction refinement iterations and the inference of many redundant predicates.

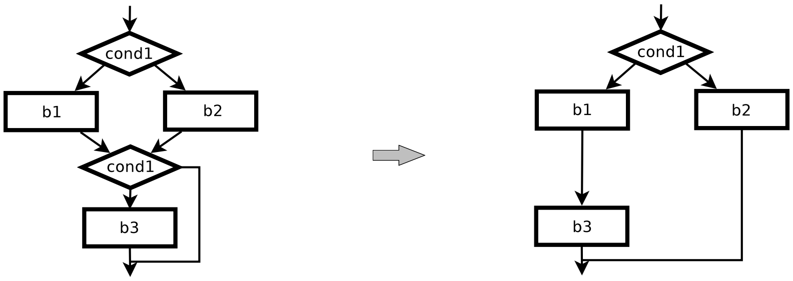


Figure 3: CFG transformation example.

4.2 Checking liveness

As SatAbs is restricted to analysis of safety properties, the Goanna tool comes into play for analysis of liveness properties. Goanna is a C and C++ bug finding tool that supports user-defined rules written in the CTL temporal logic [10], which allows natural specification of safety and liveness properties. Unlike SatAbs, Goanna is intended as a fast compile-time checker and therefore does not perform data-flow analysis.

Properties to be checked for each protocol are extracted from the protocol specification. In particular, we apply the *AWAIT1* rule to every incoming mailbox and the *Timed* rule to every timed state of the protocol.

Describing a temporal property using the Goanna specification language involves two steps. First, we identify a set of important program events related to the property being verified, such as sending and receiving of messages. We use syntactic pattern matching to label program locations that correspond to these events. Second, we encode the property to be checked as a temporal logic formula in a dialect of CTL, defined over events identified at the previous step. Due to limited space, we omit the details of this encoding.

5 Implementation

We implemented the active driver framework along with three active device drivers in Linux 2.6.38. The framework consists of loadable kernel modules and does not require any changes to other kernel components. The framework provides services required by all active drivers, including cooperative scheduling, message passing, and message-based interrupt delivery. In addition it defines protocols for supported classes of drivers and provides wrappers to perform the translation between the Linux driver interface and message-based active driver protocols. Wrappers enable conventional and active drivers to co-exist within the kernel.

The generic part of the framework shared by all active drivers provides support for scheduling and message passing. It implements the *cooperative domain* abstraction, which constitutes a collection of cooperatively scheduled kernel threads hosting an active driver. Threads inside the domain communicate with the kernel via a shared message queue. The framework guarantees that at most one thread in the domain is runnable at any time. The thread keeps executing until it blocks in the `AWAIT` function. `AWAIT` checks whether there is a message available in one of the mailboxes specified by the caller and, if so, returns without blocking. Otherwise it calls the thread dispatcher function, which finds a thread for which a message has arrived. The dispatcher uses the kernel scheduler interface to suspend the current thread

driver protocol	**#states**	**#transitions**	**#subprotocols**
PCI bus	13	41	11
Ethernet	17	36	6
Serial ATA (SATA)	39	70	22
Digital Audio Interface (DAI)	8	20	6

Table 1: Implemented active driver protocols.

and make the new thread runnable. In the future this design can be optimised by implementing native support for light-weight threads in the kernel.

`EMIT` and `AWAIT` functions do not perform memory allocation and therefore never fail. This simplifies driver development, as the driver does not need to implement error handling logic for each invocation of these ubiquitous operations. On the other hand this means that the driver is responsible for allocating messages sent to the OS and deallocating messages received from the OS. By design of driver protocols, most mailboxes can contain at most one message, since the sender can only emit a new message to the mailbox after receiving a completion notification for the previous request. Such messages can be pre-allocated statically.

Interrupt handling in active drivers is separated into top and bottom halves. The driver registers with the framework a top-half function that is invoked by the kernel in the primary interrupt context (outside the cooperative domain). A typical top-half handler reads the interrupt status register, acknowledges the interrupt in the device, and sends an IRQ message to the driver. The actual interrupt handling happens inside the cooperative domain in the context of the driver thread that receives the IRQ message. IRQ delivery latency can be minimised by queueing interrupt messages at the head of the message queue; alternatively interrupts can be queued as normal messages, which avoids interrupt livelock an ensures fair scheduling of interrupts with respect to other driver tasks.

In addition to the generic functionality described above, the active driver framework defines protocols for supported classes of drivers and provides wrappers to perform the translation between the Linux driver interface and message-based active driver protocols. Wrappers enable conventional and active drivers to co-exist within the kernel.

Active driver protocols are derived from the corresponding Linux interfaces by replacing every interface function with a message or a pair of request/response messages. While multiple function calls can occur concurrently, messages are serialised by the wrapper.

Since Linux lacks a formal or informal specification of driver interfaces, deriving protocol state machines often required tedious inspection of the kernel source. On the positive side, we found that, compared to building an OS model as a C program, state machines provide a natural way to capture protocol constraints and are useful not only for automatic verification, but also as documentation for driver developers.

Table 1 lists protocols we have specified and implemented wrappers for. For each protocol, it gives the number of protocol states and transitions, and the number of subprotocols in its decomposition (see Section 4.1). Table 2 lists active device drivers we have implemented along with protocols that each driver supports. All three drivers control common types of devices found in virtually every computer system. These drivers were obtained by porting native Linux drivers to the active architecture, which allows direct comparison of their performance and verifiability against conventional drivers.

driver	**supported protocols**	**LOC (native)**	**LOC (active)**	**avg(max) time(minutes)**	**avg(max) refinements**	**avg(max) predicates**
RTL8169 1Gb Ethernet	PCI, Ethernet	4,220	4,317	29 (103)	3 (7)	3 (8)
AHCI SATA controller	PCI, SATA	2,268	2,487	123 (335)	2 (6)	2 (19)
OMAP DAI audio	DAI	583	705	5 (13)	2 (5)	2 (0)

Table 2: Active device driver case studies, protocols that each driver implements, size of the native Linux and active versions of the driver in lines of code (LOC) (measured using `sloccount`), along with statistics for checking safety properties using SATABS for each driver.

6 Evaluation

6.1 Verification

We applied the verification methodology described in Section 4 to RTL8169, AHCI, and OMAP DAI drivers. Verification was performed on machines with 2GHz quad-core Intel Xeon CPUs.

Verification using SATABS and GOANNA For each of the three drivers we were able to verify all safety properties defined by their protocols using SATABS with zero false positives. The last three columns of Table 2 show statistics for verifying safety properties using SATABS for each driver: average and maximum time, the number of abstraction refinement loop iterations and the number of predicates required for verification to succeed, across all subprotocols of the driver. The number of predicates reflects predicates discovered dynamically by the abstraction refinement loop and does not include candidate predicates with which SATABS is initialised (see Section 4.1).

The small number of predicates involved in checking these properties indicates that the control skeleton of an active driver responsible for interaction with the OS has few data dependencies. This confirms that the active driver architecture achieves its goal of making the driver-OS interface amenable to efficient automatic verification. At the same time, the fact that several refinements are required in most cases indicates that the power of the abstraction refinement method is necessary to avoid false positives when checking safety.

Despite the small number of predicates required, verification times are relatively high for our benchmarks. This is due to the large size of our drivers, and the fact that SMV [20], the model checker used by SATABS, was not designed primarily for model checking boolean programs. We experimented with the BOOM model checker [5], which is geared towards boolean program verification. While in many cases verification using BOOM was several times faster than with SMV, we did not use it in our final experiments due to stability issues.

All optimisations described in Section 4.1 proved essential to making verification tractable. Disabling any one of them led to overly large abstractions that could not be analysed within reasonable time.

We used GOANNA to verify liveness properties of drivers as explained in Section 4.2. GOANNA performs a less precise analysis than SATABS and is therefore much faster. It verified all drivers in less than 1 minute while generating 8 false positives due to imprecise data flow analysis.

These results demonstrate that active drivers' protocol compliance can be verified using existing tools. At the same time they suggest that an optimal combination of accuracy and verification time requires a trade-off between full-blown predicate abstraction of SATABS and purely syntactic analysis of GOANNA.

Comparison with conventional driver verification In order to compare the effectiveness of our verification methodology against conventional verification techniques for passive drivers, we carried out a case study using the native Linux version of the RTL8169 Ethernet controller driver. We analysed the history of bug fixes made to this driver, and identified those fixes that address OS interface violation bugs. A typical example involves the driver attempting to use an OS resource such as timer after it has been destroyed by a racing thread. We found 12 such bugs. We apply SATABS to detect these bugs. SATABS has been successfully applied to Linux drivers in the past [22]. Using SATABS as a model checker for both active and traditional drivers provides a fair comparison.

Detecting OS interface bugs in a passive driver requires a model of the OS. We built a series of such models of increasing complexity so that each new model reveals additional errors but introduces additional execution traces and is therefore harder to verify. This way we explore the best-case scenario for the passive driver verification methodology: using our knowledge of the error we tune the model for this exact error. In practice more general and hence less efficient models are used in driver verification.

By gradually improving the OS model, we were able to find 8 out of 12 bugs. However, when being provided a model accurate enough to trigger the remaining 4 errors, SATABS was not able to find the bugs before being interrupted after 12 hours.

We carried out an equivalent case study on the active version of the RTL8169 driver. To this end, we simulated the 12 OS protocol violations found in the native Linux driver in the active driver. We were able to detect each of the 12 protocol violation bugs within 3 minutes per bug. This result confirms that the active driver architecture along with the verification methodology presented above lead to device drivers that are more amenable to automatic verification than passive drivers.

6.2 Performance

Microbenchmarks The performance of active drivers depends on the overhead introduced by thread switching and message passing. We measure this overhead on a machine with 2 quad-core 1.5GHz Xeon CPUs.

In the first set of experiments, we measure the communication throughput by sending a stream of messages from a normal kernel thread to a thread inside a cooperative domain. Messages are buffered in the message queue and delivered in batches when the cooperative domain is activated by the scheduler. This setup simulates streaming of network packets through an Ethernet driver. The achieved throughput is $2 \cdot 10^6$ messages/s (500 ns/message) with both threads running on the same core and $1.2 \cdot 10^6$ messages/s (800 ns/message) with the two threads assigned to different cores on the same chip.

Second, we run the same experiment with varying number of kernel threads distributed across available CPU cores (without enforcing CPU affinity), with each Linux thread communicating with the cooperative thread through a separate mailbox. As shown in Figure 4, we do not observe any noticeable degradation of the throughput or CPU utilisation as the number of clients contending to communicate with the single server thread increases (the drop between one and two client threads is due to the higher cost of inter-CPU communication). This shows that our implementation of message queueing scales well with the number of clients.

Third, we measure the communication latency between a Linux thread and an active driver thread running on the same CPU by bouncing a message between them in a ping-pong fashion. The average measured roundtrip latency is 1.8 μs. For comparison, the roundtrip latency of a Gigabit network link is at least 55μs [19].

Macrobenchmarks We compare the performance of the active RTL8169 Ethernet controller driver against equivalent native Linux driver using the Netperf benchmark suite on a 2.9GHz quad-core Intel Core i7 machine. Results of the comparison are shown in Figure 5. In the first set of experiments

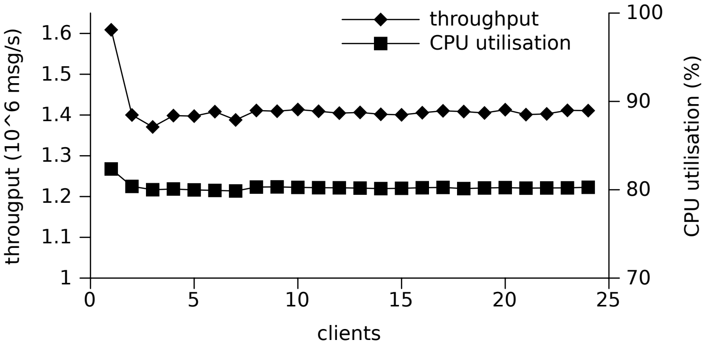
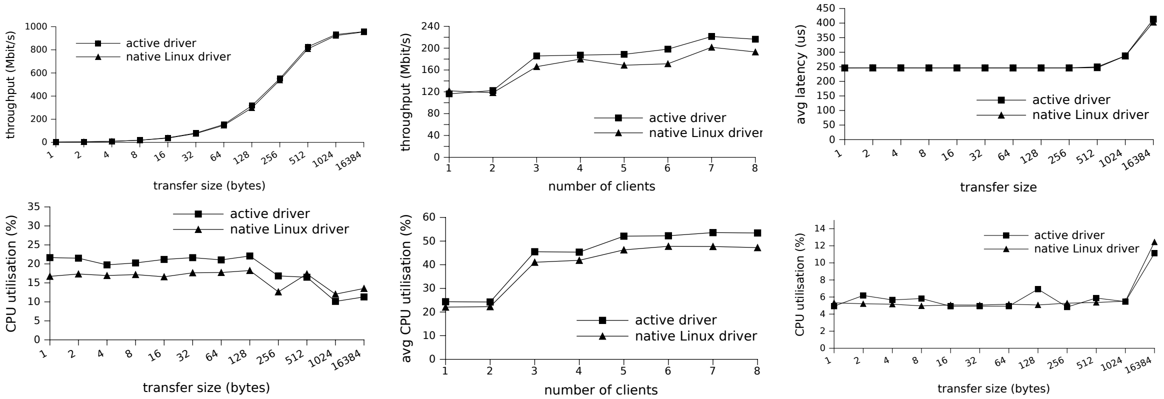


Figure 4: Message throughput and aggregate CPU utilisation over 8 CPUs for varying number of clients.



(a) UDP throughput for varying packet sizes for a single client. The top graph shows achieved throughput; the bottom graph shows CPU utilisation.

(b) UDP throughput for multiple clients (packet size=64 bytes). The top graph shows aggregate throughput; the bottom graph shows average CPU utilisation across 8 cores.

(c) UDP latency for varying packet sizes for a single client. The top graph shows average round-trip latency; the bottom graph show CPU utilisation.

Figure 5: Performance of the RTL8169 Ethernet driver measured with Netperf.

we send a stream of UDP packets from the client to the host machine, measuring achieved throughput (using Netperf) and CPU utilisation (using `oprofile`) for different payload sizes. The client machine is equipped with a 2GHz AMD Opteron CPU and a Broadcom NetXtreme BCM5704 NIC. The active driver achieved the same throughput as the native Linux driver on all packet sizes, while using 20% more CPU in the worst case (Figure 5(a)).

In the second set of experiments, we fix payload size to 64 bytes and vary the number of clients generating UDP traffic to the host between 1 and 8. The clients are distributed across four 2GHz Intel Celeron machines with an Intel PRO/1000 MT NIC. The results (Figure 5(b)) show that the active driver sustains up to 10% higher throughput while using proportionally more CPU. Further analysis revealed that the throughput improvement is due to slightly higher IRQ latency, which allows the driver to handle more packets per interrupt, leading to lower packet loss rate.

The third set of experiments measures the round trip communication latency between the host and a remote client with 2GHz AMD Opteron and NetXtreme BCM5704 NIC. Figure 5(c) shows that the latency introduced by message passing is completely masked by the network latency in these experiments.

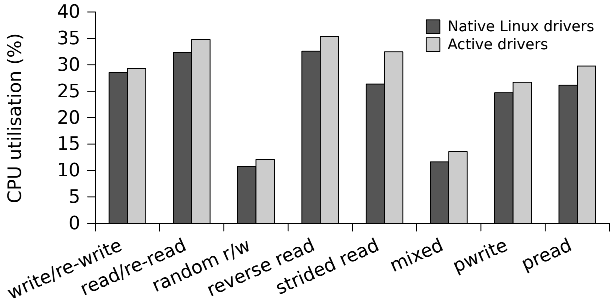


Figure 6: Native vs. active AHCI and ATA framework driver performance on the iozone benchmark.

We evaluate the performance of the AHCI SATA controller driver using the `iozone` benchmark suite running on a system with a 2.33GHz Intel Core 2 Duo CPU, Marvell 88SE9123 PCIe 2.0 SATA controller, and WD Caviar SATA-II 7200 RPM hard disk. We run the benchmark with working set of 500MB on top of the raw disk.

We benchmark the driver against equivalent Linux driver. Both drivers achieved the same I/O throughput on all tests, while the active driver's CPU utilisation was slightly higher (Figure 6). This overhead can be reduced through improved protocol design. Our SATA driver protocol, based on the equivalent Linux interface requires 10 messages for each I/O operation. A clean-slate redesign of this protocol would involve much fewer messages.

We did not benchmark the DAI driver, as it has trivial performance requirements and uses less than 5% of CPU.

7 Related work

Active drivers Singularity [12] is a research OS written in the Sing# programming language. It comprises a collection of processes communicating over message channels. Sing# supports a state-machine-based notation for specifying communication protocols between various OS components, including device drivers. The Sing# compiler checks protocol compliance at compile time. RMoX [4] is a process-based OS written in occam-pi. RMoX processes communicate using synchronous rendezvous. Communication protocols are formalised using the CSP process algebra and verified using the FDR tool.

The Dingo [21] active driver framework for Linux aims to simplify driver programming in order to help driver developers avoid errors. It relies on a C language extension to provide language-level support for messages and threads. Dingo uses a Statechart-based language to specify driver protocols; however it only supports runtime protocol checking and does not implement any form of static verification.

The CLARITY [6] programming language is designed to make passive drivers more amenable to automatic verification. To this end it provides constructs that allow writing event-based code in a sequential style, which reduces stack ripping. It simplifies reasoning about concurrency by encapsulating thread synchronisations inside *coord* objects that expose well-defined sequential protocols to the user.

Verification tools Automatic verification tools for C [3, 9, 8, 16]is an active area of research, which is complementary to our work on making drivers amenable to formal analysis using such tools. Several verification tools, including SPIN [18], focus on checking message-based protocols in distributed systems. These tools work on an abstract model of the system that is either written by the user or extracted from the program source code [17]. Such a model constitutes a fixed abstraction of the system that cannot be automatically refined if it proves too coarse to verify the property in question. Our experiments show that abstraction refinement is essential to avoiding false positives in active driver verification; therefore we do not expect these tools to perform well on active driver verification tasks.

8 Conclusion

Improvements in automatic device driver verification cannot rely solely on smarter verification tools and require an improved driver architecture. Previous proposals for verification-friendly drivers were based on specialised language and OS support and were not compatible with existing systems. Based on ideas from this earlier research, we developed a driver architecture and verification methodology that can be implemented in any existing OS. Our experiments confirm that this methodology enables more thorough verification of the driver-OS interface than what is possible for conventional drivers.

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