SMoTherSpectre: Exploiting Speculative Execution through Port Contention

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ABSTRACT
Spectre, Meltdown, and related attacks have demonstrated that kernels, hypervisors, trusted execution environments, and browsers are prone to information disclosure through micro-architectural weaknesses. However, it remains unclear as to what extent other applications, in particular those that do not load attacker-provided code, may be impacted. It also remains unclear as to what extent these attacks are reliant on cache-based side channels.

We introduce SMoTherSpectre, a speculative code-reuse attack that leverages port-contention in simultaneously multi-threaded processors (SMoTher) as a side channel to leak information from a victim process. SMoTher is a fine-grained side channel that detects contention based on a single victim instruction. To discover real-world gadgets, we describe a methodology and build a tool that locates SMoTher-gadgets in popular libraries. In an evaluation on glibc, we found hundreds of gadgets that can be used to leak information. Finally, we demonstrate proof-of-concept attacks against the OpenSSH server, creating oracles for determining four host key bits, and against an application performing encryption using the OpenSSL library, creating an oracle which can differentiate a bit of the plaintext through gadgets in libcrypto and glibc.

CCS CONCEPTS
- Security and privacy → Side-channel analysis and countermeasures.

KEYWORDS
side-channel; simultaneous multithreading; speculative execution; attack; microarchitecture

1 INTRODUCTION
Spectre [23, 24, 29] and Meltdown [26] form a new class of micro-architectural attacks. These attacks leverage weaknesses in speculative execution (Spectre) or separation between privileged and unprivileged code (Meltdown) to leave micro-architectural traces [5]. Both Spectre and Meltdown leverage a side channel based on the memory architecture to leak data from the address space of a target (e.g. from another process or from the kernel).

While micro-architectural side channels were known before the discovery of Meltdown and Spectre, their applicability was mostly limited to targets applying data-dependent control flow patterns or memory accesses. In this older class of vulnerabilities, an attacker would observe the micro-architectural changes to shared resources caused by the execution of a victim. For example, in a cache-based attack, the adversary would prime the cache, let the victim execute, and then detect which locations have been evicted from the cache. Such a side channel leaks addresses and allows the adversary to learn information from data-dependent execution. An effective mitigation strategy is to eliminate data-dependent control flow over sensitive data, such as cryptographic material.

In contrast, Spectre and Meltdown render this class of attacks generic and significantly harder to mitigate through software changes only. The side channel is now used indirectly, in a way that – crucially – does not rely on poor choices in the development of the target application. In Spectre, for instance, the attacker first primes the speculation engine (e.g., by preparing the branch target buffers) as well as the cache-based side channel; the victim then misspeculates at an attacker-controlled location and thereby leaks information [5]. The attacker can then read out the cache-based side channel. In light of these new attack vectors, architectural, system-wide defenses such as Kernel Page-Table Isolation [15], retpolines [33], or microcode updates must be rolled out to protect the system against attacks. One proposed microarchitectural defense is to revert all side effects of speculative execution [21].
One mitigating factor is that so far, with the exception of Netspectre-AVX [29], all existing attacks rely on side channels that are invariably cache-based to read out information. This in turn requires the presence of specific gadgets in the victim, which are often hard to find. Consider the example of Branch Target Injection (BTI), the technique used in Spectre v2 [23]: in the initial exploit, no suitable gadget was identified in the kernel. The attack was successful because it redirected speculative control flow to externally provided code, in the form of eBPF kernel code. This observation justifies why mitigations such as retopline are not employed at large by user-space programs.

In this paper, we show that speculation attacks (e.g., through branch target injection) can leak arbitrary secrets from generic user-space programs through a side channel that is not based on the memory architecture. In particular, we show that branch target injection can be used on existing program code, without requiring the injection of attacker code. To this end, we first show that port contention can be used as a powerful side channel when executing with simultaneous multi-threading (SMoTHER). We then exploit port contention as a side channel to transmit information during speculative execution (SMoTHERSpectre). This shows that, because the transmission occurs before speculative execution ends, reverting side effects of speculative execution would not be sufficient as a defense. Finally, we show how suitable portions of code can be found in target binaries automatically.

Other related work has looked at execution-unit-sharing as a side channel [1, 2, 11, 35]. Portsmash [2], concurrently developed to our work, demonstrates that port sharing leaks code access patterns and successfully extracts secrets from a known vulnerable version of OpenSSL. We are, however, the first to characterize this side channel and leverage it for a speculative execution attack, providing a full working proof of concept that leaks data from an up-to-date OpenSSL version. Further, we attack the OpenSSH server, leaking bits from the host’s RSA key.

This paper makes the following contributions:

- A precise characterization of the port-contention side channel (SMoTHER);
- A speculative execution attack (SMoTHERSpectre) that demonstrates the suitability of non-cache-based side channels to leak information. We show an end-to-end attack using speculation based on BTI by combining it with the port contention side channel;
- An automated technique to find target speculative gadgets in programs; and
- Real world attacks where we target BTI gadgets in the OpenSSH server and in the latest version of OpenSSL, along with a SMoTHER gadget from the libc.

2 BACKGROUND

The work in this paper relies on the complex interplay between software and hardware. In the following, we provide the background information necessary to understand SMoTHER and SMoTHERSpectre.

CPU Microarchitecture. A modern CPU is typically split into two main components: the frontend and the backend (or execution engine). The frontend predicts where to fetch instructions from and creates a program-order stream of instructions to be executed by the backend. The instructions are either decoded and executed ‘as-is’ in RISC ISAs (e.g., IBM POWER or ARM) or broken down into RISC-like instructions called μops in CISC ISAs (e.g., x86 or IBM Z). For brevity we refer to all instructions executed by the backend as μops. Once fetched and decoded, the μops are placed in an instruction window (also referred to as issue queue or reservation stations) to be scheduled and dispatched to execution units when their operands are ready. Every cycle, the scheduler searches the instruction window to identify which μops are ready for execution and which execution unit is available to dispatch them to. μops can execute out of program order (e.g., a later μop in program order can execute earlier) if their operands are ready and a relevant execution unit is available. Ideally, all execution units would be designed to handle every type of operation to maximize throughput. In practice, execution units are specialized and only the more commonly used ones are replicated. A group of execution units share a port, indicating their availability in a given cycle. Contention for a port leads to delays in execution. Figure 1 demonstrates scheduling instructions from an execution window containing three μops, where contention for port 3 prevents the second μop from being scheduled in the same cycle as the other two.

Speculative Execution. Because the stream of μops is predicted but is not guaranteed to execute, complete and make its state visible to software, the backend also contains a re-order buffer that commits the state of each completed μop in program order to the software visible structures (i.e., register file and memory). This execution of μops is speculative because the frontend may have mispredicted the direction and/or the target address of a branch operation. Upon mis-prediction, the pipeline flushes all μops in the re-order buffer and restarts fetching and decoding μops. While executing on the mis-predicted path, the processor accesses the cache hierarchy leaving side-effects which lead to cache-based side channels even though the values accessed are discarded and do not impact the executing software.

Simultaneous Multithreading. Out-of-order processors provide a large fraction of silicon area to mechanisms that exploit speculation and parallelism in execution. While these mechanisms are designed for peak parallelism, most structures (e.g., execution
will need to fetch that value and cause the corresponding memory works for both conditional branches as well as indirect branches. Execution units. Instructions that are scheduled to execute on the architectural state, even if it has none on the architectural state. For such that it is tricked into predicting the wrong target for a branch. Because branch direction history (i.e., taken or not taken) is a shared resource, an attacking process can prime the branch predictor of its victim. Similarly, a branch target buffer predicting the target address for a branch can be primed by an attacking process. This works for both conditional branches as well as indirect branches. In a conditional branch, such as an array-size check in Spectre V1, the CPU can be tricked into speculatively executing an out-of-bounds array access in spite of the failing length check. If the target address of the length check is not in the cache then the memory fetch will take longer than the following speculatively executed instructions. In an indirect branch, the CPU can be tricked into speculatively executing arbitrary code in a victim process by providing a malicious branch history through a temporally or spatially (in the case of SMT) co-located attacker process. We discuss related work in Section 7.

**Speculative Execution Attacks.** Speculative execution can be exploited by priming the branch predictor with sufficient history such that it is tricked into predicting the wrong target for a branch. Because branch direction history (i.e., taken or not taken) is a shared resource, an attacking process can prime the branch predictor of its victim. Similarly, a branch target buffer predicting the target address for a branch can be primed by an attacking process. This works for both conditional branches as well as indirect branches. In a conditional branch, such as an array-size check in Spectre V1, the CPU can be tricked into speculatively executing an out-of-bounds array access in spite of the failing length check. If the target address of the length check is not in the cache then the memory fetch will take longer than the following speculatively executed instructions. In an indirect branch, the CPU can be tricked into speculatively executing arbitrary code in a victim process by providing a malicious branch history through a temporally or spatially (in the case of SMT) co-located attacker process. We discuss related work in Section 7.

**Cache-timing Side Channel.** Speculative execution attacks, such as Spectre, exploit the fact that a speculative execution and then discarded operation does have side effects on the micro-architectural state, even if it has none on the architectural state. For example, an instruction that operates on a value stored in memory will need to fetch that value and cause the corresponding memory region to be pulled into the cache. The side-effect that the memory region is now cached is not undone when the instruction is discarded instead of retired, and can be measured using cache side channels. For example, in Spectre V1 the victim code uses two dependent array lookups, where the result of the lookup of the first array is used as an index into the second array. This index can be leaked by measuring access times to the second array through a flush and reload attack. By ensuring that the second array is flushed from the cache before the victim code executes, and measuring the access times afterwards, only the lookup of the index that has been used by the victim code will be significantly faster.

3 **SMOTHER**

In this section, we describe and evaluate SMoTher, a side channel based on port-contention, present in SMT architectures. SMoTher is based on the following observation: two co-located (i.e., running on the same physical core) hardware threads of execution share execution units. Instructions that are scheduled to execute on the same execution port will contend for the available resources. We show how this contention can be measured, at first in a coarse-grained way, i.e., with large sequences of instructions scheduled on the same port on both threads, and then in a fine-grained way, i.e., with minimal sequences of instructions. The result is that an unprivileged attacker process can detect whether a co-located victim process is running an instruction on a given port.

### 3.1 Ideal covert channel

In this experiment, we demonstrate port contention between two threads running simultaneously on the same physical core and describe how it can be measured in ideal conditions.

#### 3.1.1 Experiment design

Executing instructions that occupy a specific port and measuring their timing enables inference about other instructions executing on the same port. We first choose two instructions, each scheduled on a single, distinct, execution port. One thread runs and times a long sequence of single microop instructions scheduled on port \( a \), while simultaneously the other thread runs a long sequence of instructions scheduled on port \( b \). We expect that, if \( a = b \), contention occurs and the measured execution time is longer compared to the \( a \neq b \) case.

#### 3.1.2 Experimental setup

We run experiments on an Intel Core i7-6700K CPU running Ubuntu 16.04.4 stock kernel, version 4.15.0. Both attacker and victim are pinned to different hardware threads on the same physical core. The CPU governor is set to Performance for a constant clock frequency. The “performance” state is configured below the turbo frequency range to lower non-deterministic factors in the environment. Apart from these changes, all other settings are kept to their defaults. Most notably, speculative-execution-related mitigations are left enabled.

In the measuring thread, we execute and time a sequence of 1,200 \( shl \), a single \( microop \) instruction that executes on port \( 0 \) or port \( 6 \), which we denote port \( 06 \), on this CPU. The colocated thread runs a sequence of either 1,200 \( shl \) or \( popcnt \) instructions: the \( shl \) instructions directly contend for port \( 06 \) while the \( popcnt \) instructions will introduce no contention as they execute only on port \( 1 \). Instruction-to-port mappings are available through reverse engineering [10] or the Intel Architecture Code Analyzer (IACA) tool.

#### 3.1.3 Results and discussion

We report averages over 10,000 runs, together with a 95%-confidence interval calculated using the Student’s t-distribution. The experiment successfully demonstrates that port contention occurs and that the SMoTher side channel can be used to extract information, as we can see in Table 1. Indeed, the run time of the contention experiment is about twice of the non-contended one. This indicates that port contention is likely the main bottleneck in this experiment.

This result shows how SMoTher can be used as a reliable covert communication channel between two co-located threads. However, as this experiment requires precisely choosing the type and number of instructions running in one of the two threads, it is yet unclear if port contention may serve as a practical side channel. We explore this aspect in the next section.
### 3.2 Characterization of the side channel

We now analyse whether SMOTHE is effective as a side channel for distinguishing realistic sequences of instructions on a simultaneously executing, co-located victim process. Specifically, we want to explore whether an attacker can distinguish between the different sequences of instructions from a known set which the victim may run. To encapsulate this property of the set, we define the term **SMOTHE-differentiability**.

**SMOTHE differentiability.** Let us consider that the victim runs one sequence out of a set \( V = \{ V_0, V_1, \ldots \} \). The attacker is allowed to craft any sequence of instructions \( A \) and time multiple iterations of \( A \) running concurrently with the victim. If the attacker can infer which sequence \( V_i \in V \) the victim was running based on its timing measurements, the sequences in \( V \) are said to be SMOTHE-differentiable. On its part, the attacker has a-priori knowledge of what timing to expect when \( A \) runs concurrently with each of \( V_i \in V \). It can use experiments in a similar, but controlled, environment to generate this knowledge. Further, the attacker is allowed to use any statistical test or metric to make its decision. Examples of such metrics include the mean or the median of the timings, or their distributions.

In experiments in later sections of this paper, we shall establish various pairs of sequences to be SMOTHE-differentiable. After collecting attacker timings distributions for each victim sequence in our controlled environment, we shall use the Student’s t-test to establish statistical difference between them with at-least 95%-confidence. We argue that an attacker, in an adversarial scenario, can correlate its own timing distribution with either of the a-priori distributions to identify the victim sequence.

At its core, SMOTHE-differentiability implies that the sequences in \( V \) have differing degrees of utilization on some specific port(s) and vice-versa. The attacker would ideally choose a sequence of instructions scheduled solely on these ports to maximize the chance of encountering different levels of contention across the different possible \( V_i \). Through our experiments, we wish to explore how short SMOTHE-differentiable sequences can be and the ideal length of attacker sequences to differentiate them.

**Experiment design and setup.** In our first experiment, we consider a victim running sequences of either `popcnt` (port 1) or `ror` (port 06) and an attacker timing a sequence of `popcnt`. We vary the length of both attacker and victim sequences, and check for SMOTHE-differentiability by noting the percentage change in mean execution time for the attacker. In a second experiment, the victim runs either `cmove` (port 06) instructions or `popcnt`. In this case, the attacker times a sequence of `bts` (port 06) instructions with both operands as registers.

| Experiment | Execution Time (cycles) |
|------------|-------------------------|
| Port contention | 1214 ± 67 |
| No port contention | 674 ± 13 |

Table 1: Port contention covert channel: a thread running a long sequence of port 06 instructions is twice as slow when a co-located thread executes a long sequence of port 06 instructions, when compared to a co-located thread executing a long sequence of port-1-only instructions.

To run this experiment, an orchestrator process is used to fork the victim and attacker processes, and to set their core affinities so that they share a physical core. We require the execution of the target sequence in the victim to temporally overlap with the (timed) execution of the attacker sequence to assure port contention. Therefore, the processes use a synchronization barrier which ensures that any following instructions will be run concurrently. Thereafter, each process runs their respective sequence, using `rdtscp` to take timestamps at the beginning and end of each run. The timestamps tell us the number of cycles taken to execute the sequence and were used to also check that the executions were properly synchronized. Atomic operations on variables in shared memory were used to implement the synchronization. We repeat this process to collect multiple timing samples.

In this set of experiments, we keep the same hardware and OS configuration as used in the covert channel experiment, while precisely controlling the synchronization of threads through the additional instrumentation described above.

**Results.** Figure 2 plots the average difference in attacker execution time between the two sequences of victim instructions for each experiment. The length of the sequence for the victim was taken from the set \( \{1, 4, 8, 16, 32\} \) while the attacker sequence varied in length between one and 100 instructions.

Our measurements confirm that timing short sequences of instructions is feasible: for a vast majority of sequence-length combinations the victim sequences were SMOTHE-differentiable using the Student’s t-test on the attacker’s running time distributions. While timing `popcnt`, 83% of all combinations plotted in Figure 2a showed significant differences in means between the victim’s sequences of `popcnt` and `ror`.

The measured differences vary from close to 0% to 40%. Longer sequences of instructions in the victim lead to higher differences and less variability in measurements. Only 48% of `popcnt` measurements with sequence of 1 victim instruction are SMOTHE-differentiable, as opposed to 83% for a sequence of 4, and 100% for a sequence of 32 victim instructions. This means that distinguishing a sequence of one victim instruction (max. 9% difference and more variability) is much harder than a sequence of 32 victim instructions (max. 38% difference and less variability).

We observe that there is an optimal number of attacker instructions to measure a victim instruction sequence of a given length, which increases with the number of victim instructions: from 10 attacker instructions for one victim instruction to 45 instructions for 32 victim instructions. This is explained by the following observations: contention for longer instruction sequences in the attacker is easier to time, since attacker and victim sequences are more likely to overlap. This effect fades when the attacker sequence becomes significantly longer than the victim’s, at which point only a small portion of the executed instructions will contend, thereby leading to a smaller difference.

To show the breadth of possible SMOTHE-differentiability results, we perform a second experiment, with a victim running instructions which may be scheduled to more than one port. Specifically, the victim runs either `cmove` (port 06) or `popcnt` (port 1). The attacker times a sequence of `bts` instructions (port 06) to measure the contention on ports zero and six. Figure 2b shows that multiport instructions are still SMOTHE-differentiable. However, variance is
we have noted a number of takeaways and pitfalls to avoid during practice, this means the attacker may need more runs to extract information, and the choice of the number of attacker instructions is more important than in the previous experiment. As in the previous experiment, we observe that the optimal number of attacker instructions increases with the number of victim instructions. Beyond this number, most experiments show lower SMoTher-differentiability, with most between 0 and 5%.

While our results show that the SMoTher side channel exists and can be measured even for a small sequence of instructions, we have noted a number of takeaways and pitfalls to avoid during measurements, namely:

- Synchronisation of the target code sequence in the victim and the timed code sequence in the attacker is extremely important, more so when the target code sequence in the victim is short;
- Pipeline bottlenecks other than port contention may occur and overshadow the side channel. One such example is read-after-write hazards;
- The CPU may eliminate the execution of some instructions based on their operands (one such case is zero idioms). This results in those operands not being executed, and removing contention;
- Some instructions (e.g., those from the SSE and AVX extensions) are subject to aggressive power-saving features on modern CPUs. This makes measuring port contention more difficult (and the power savings may in fact serve as its own side channel [29] separately from SMoTher).

Finally, we note that practical instruction sequences are unlikely to be identical repeated instructions. However, this is not required for practical SMoTher side channels: it is only required that, among a sequence of instructions, they exercise different degrees of port pressure on the port that the attacker is measuring. We further expand on this idea in Section 5 for practical SMoTher-differentiable sequences.

4 SMOTHERSPECTRE

SMoTherSpectre is a speculative code-reuse attack technique which starts at an indirect jump on the victim’s usual execution path. The attacker leverages Branch Target Injection (BTI) to “poison” the CPU’s branch predictor such that when the victim’s fetch unit asks for the target of the indirect jump, it is sent the address of a separate data-dependent conditional jump within the victim’s binary with SMoTher-differentiable fall-through and target sequences. During the period of the speculative execution, the victim evaluates the condition and jumps to either the target or fall-through sequences. The attacker times a sequence of relevant instructions to identify which sequence is run on the victim (SMoTher), thereby inferring the outcome of the condition and learning some information about the victim’s data.

SMoTherSpectre complements and extends existing attacks [5, 23, 24] which use cache-based side channels to exfiltrate secrets. Using such channels implies that these exploits i) require the presence of special gadgets in the victim code, or the ability to inject them; and ii) depend on speculative execution leaving persistent, measurable microarchitectural side-effects.

Calls using function pointers in C/C++ are traditionally implemented by indirect calls in assembly. While exploitable indirect jumps are prevalent in most programs, the first observation limits the set of available gadgets for ultimately leaking secrets. This scarcity, along with the overheads of some software-only mitigations, justifies the use of user-space programs to not deploy countermeasures such as retropoles or STIBP by default. In contrast, SMoTher-differentiable gadgets are easily found (as we demonstrate in Section 5). Almost every conditional jump can be part of a SMoTher-gadget, requiring only its fall-through and target to be

(a) SMoTher attack using popcnt to detect if the co-located victim runs on port 1.

(b) SMoTher attack using bts to detect if the co-located victim runs on port 06.

Figure 2: SMoTher side channel characterization. Each data point represents the difference between the average execution time of the attacker thread, between the port contention scenario and the baseline. We do not plot the few data points where Student’s t-test shows no statistically significant difference between both distributions at 95%-confidence. The data points for which the attacker runs fewer instructions than the victim are plotted in grey.
4.1 Attacker model

The objective of a SMoTherSpectre adversary is to extract secret information from a victim process and we make the following assumptions about the attacker: i) they control code in a process co-located with the victim process; ii) they can launch branch target injection attacks.

The first assumption is justified: if the attacker can execute code on the same machine of the victim, the scheduler may schedule the attacker and victim on two different threads of the same physical core. An example of such colocaction may exist in public cloud offerings where compute resources are shared at a fine granularity between tenants: for IaaS, virtual cores for different customers may map to the same physical core, for PaaS/SaaS processes for different tenants may be similarly scheduled [4, 13].

Existing mitigations against BTI include software (retpolines) and a set of hardware interfaces for flushing the indirect branch predictors at the appropriate times and for not sharing them across SMT threads (IBRS, IBPB and STIBP in Intel). These mitigations come with a potentially severe performance impact [31]. As such, these controls have been enabled only for selected system components such as the kernel, and none of the user-space programs we have analysed make use of them. The adversary also needs to know the victim’s code base, which is possible through the use of common libraries and open-sourced applications, and where it is located in memory. It must be able to circumvent ASLR and similar controls: the literature contains several examples [9, 19, 30] of how this is achievable in practice, including an approach using the same BTB weaknesses that make BTI possible.

4.2 Attack principle

Figure 3 shows a side-by-side layout of the code of a victim and an attacker in the SMoTherSpectre setting. As the figure shows, the attack requires two types of gadgets in the victim code:

- A BTI gadget: Stores secret data into memory or a register (called the SMoTherSpectre target) followed by an indirect branch that can be poisoned by the attacker;
- A SMoTher gadget: A data-dependent conditional jump whose control variable is the SMoTherSpectre target, with SMoTher-differentiable (see Section 3.2) target and fall-through code paths.

The example BTI gadget in Figure 3 stores the secret into the register rdi, a pointer into rax and finally jumps to the location pointed to by rax. The corresponding SMoTher gadget contains an rdi-dependent conditional branch where the jump target and fall-through contain SMoTher-differentiable instruction sequences (popcnt and ror).

Note an important difference between traditional data-dependent control flow sequences and SMoTherSpectre. Data-dependent control flow sequences over confidential data are considered vulnerabilities, especially when found in cryptographic libraries. SMoTherSpectre does not require such a vulnerability to be present in the victim. It connects the loading of a secret variable to a register or memory location (BTI gadget) with an altogether independent, speculatively executed sequence, which happens to perform a compare-and-jump over that same register or memory location (SMoTher gadget). The two sets of instructions may well be entirely uncorrelated from a software development perspective, making the pattern harder, if not entirely impossible, to eliminate.

The attacker proceeds in two main steps, as shown in Figure 3: in the first phase the attacker performs traditional, Spectre v2 style BTI and then enters in a busy wait sequence, for instance a sequence of nop instructions. The purpose of the latter is to align the second phase of the attack with the speculative execution of the mark or fall-through sequence in the victim. In the second phase the attacker performs a SMoTher-style timing of a carefully selected sequence of instructions – ror in the example. The attacker then proceeds to a statistical analysis of the gathered timing information to learn one bit of information. This entire process can be repeated with different gadgets to leak different bits, and thereby reconstruct the secret. Note that while the example utilizes the indirect-branch prediction hardware to steer speculative execution to gadgets, any existing branch redirection method may be used for this purpose (for example the return stack buffer).

4.3 Characterization of the Side Channel

In our experimental testbed to characterize the SMoTherSpectre side channel, an orchestrator process forks a victim and an attacker process, pins them to two threads on the same physical core and executes an attacker and a victim process (similar to the testbed in
Section 3.2). Attacker and victim processes execute the body of a loop after synchronization using atomic operations on shared memory. The body of the loop is constructed as described in Figure 3.

In our proof-of-concept, we leverage the branch target buffer to redirect an indirect branch in the BTI gadget of the victim to the SMoTHER gadget. In order to maximize the success rate, we i) insert a series of N always-taken branches just prior to the indirect branch; ii) ensure that the addresses of the branches (including the target of BTI) are located at congruent addresses between attacker and victim; iii) disable ASLR; iv) evict the cache-line containing the indirect jump pointer. As other works have shown, the random ASLR offset can be leaked in a real-life attack [9, 30], and BTI can be performed by aliasing addresses (in the BTB) with very high success rates [18]. Therefore, we disregard these factors while creating our proof-of-concept (PoC). Evicting the jump pointer allows us to extend the duration of the victim’s speculative execution, in order to establish an upper bound for accuracy and throughput for the channel. In alternate settings, however, we notice that usual victim computation can alternate the pointer from the L1 cache. The resulting period of speculation is enough for our attack to work.

Further, we introduce instrumentation to obtain information about the success of the BTI attack. This information is supplied by the Performance Counter Monitor (PMC) infrastructure and can be obtained by using the msr kernel module. We use it to program the PMC counters to retrieve samples for the BR_MISP_EXEC.TAKEN INDIRECT_JUMP_NON_CALL_RET event, which is triggered every time the target of a taken indirect jump is mispredicted. PMC counters are sampled at the start of every loop and once more at their end. BTI is successful whenever the difference in the value of the counter is 1, given that the victim code contains only one indirect jump.

The timed instruction sequence in the attacker consists of a series of 42 crc32 instructions operating over randomly chosen, nonzero values. The victim process contains an equivalent sequence of crc32 instructions at the fall-through of the branch: given that crc32 instructions execute exclusively on port 1, if BTI is successful and the speculated conditional branch is not taken, the attacker will be competing for execution on port 1 with the attacker. The target of the branch instead contains a sequence of instruction designed to be executable on more ports (0,1,5,6) and thus display less contention with the attacker.

We collect two sets of samples: one when the victim’s secret is set to zero, and one where it is set to a nonzero value. Figure 4 shows the results of the experiment on a Skylake platform (i7-6700K). As we can see, the distributions obtained when the victim has a nonzero secret causes speculative execution to be directed to the fall-through of the branch, which we have designed with a competing sequence of crc32 instructions.

In the next phase of the attack, we use the results of this experiment as profiling information to read the side channel. To this end, a bit sequence is generated and set - bit by bit - as the secret value on the victim. Based on the results of Figure 4 we choose a time-stamp counter difference of 89 as a threshold: if the mean of the samples is higher than the threshold we conclude that the secret is 1, and 0 otherwise. The experiment is run, 5 samples each are collected for 20,000 secret bits. The attacker is able to correctly guess the victim’s secret with a success rate of over 98%. The entire experiment takes 0.83s as reported by time yielding a sample rate of 120,000 samples/second, and a leakage rate of 24,000bit/s. A similar experiment with guesses based on 1, 2, 3 and 4 samples result in accuracies of 72%, 78%, 83%, and 90% respectively. As expected, there is a trade-off between accuracy and leakage rate.

We repeated this experiment on a Haswell processor (i7-4790) using the same attacker-timed sequence and victim’s SMoTHER gadget. With a threshold of 85 cycles, the attacker was able to guess the victim’s secret bit with an accuracy of 53%, 62%, 69%, 70% and 76% based on 1, 2, 3, 4 and 5 samples respectively. We also validated the attack on a Broadwell processor (i3-5005u).

4.4 Discussion about SMoTHER-gadgets

A SMoTHER gadget is defined by two attributes: the condition on which the jump depends and the sequences on both paths following the jump. The latter determines whether the gadget can be used
in a SMoTherSpectre attack: the sequences must be SMoTher-differentiable. The former determines the information leaked by the gadget. In this section, we shall discuss some of the SMoThergadgets found in real libraries, and what they can leak.

Common instructions which set the condition flags in SMoThergadgets we found are cmp, test, add, sub. cmp-jxx sequences compare a value in a register (or loaded from memory) against other registers or against a constant. Each gadget reveals a constraint on the value. test-jxx and and-jxx sequences perform a bitwise-and of two values, setting flags based on the result. When one of the values is a constant with a single bit set, the gadget can be used to test whether specific bits are set in the first operand. Such gadgets reveal the corresponding bits to the attacker. When the second operand is not a constant, but a register whose value may be predicted or controlled, the attacker gains the power to check bits other than those specified by the constant gadgets.

Of the over 12,000 gadgets found in libcrypto, approximately:

- 2,800 are cmp operations
- 3,900 are test operations
- 1,500 are add operations
- 970 are or operations

There are around 350 cmp-jump gadgets which compare a value in a register or in memory against zero. Around a 100 gadgets, which check for greater-than/lesser-than conditions against zero, can be used to leak whether the value is positive or negative. Another 294 gadgets compare against (the constant) one, and 807 gadgets compare against other constants. Around 370 cmp-jump gadgets have a memory operand of which 118 compare with non-zero constants. 300+ gadgets compare with values on the stack, of which 33 are against non-zero constants. Of all cmp-jump gadgets, more than 400 check for signed or unsigned greater-than. The number of signed or unsigned lesser-than is about the same.

For victims running in a loop, there are cases where the register/memory state of interest will be the same across iterations. For example, a register/memory location storing a secret, cryptographic key can be expected to hold the same value across multiple calls to the encryption function. The attacker can leverage the BTI gadget to redirect the victim to different SMoTher-gadgets on different iterations, each time leaking different information about the secret. Over multiple iterations, the attacker can effectively leak multiple bits of the same secret, chaining the leaks from different SMoTher-gadgets. In Table 2, we show how many bits we can leak from the registers by chaining SMoTher-gadgets found in commonly used system libraries. To illustrate this for one specific register, Appendix A lists the gadgets which can be chained to leak 21 bits from rax.

5 GADGET DISCOVERY

As described in Section 4.2, we require two gadgets to be present in the victim code for SMoTherSpectre. We investigate the characteristics of ideal gadgets and how to find them in a given piece of code. We introduce port fingerprinting to summarize the port utilization of an instruction sequence and assess the potential to be detected using SMoTher. Port fingerprinting enables a comparison of the port utilization of two instruction sequences and rank combinations of instruction sequences based on their difference in port utilization.

**BTI Gadget.** The purpose of the BTI gadget is to pass the secret through a register to an arbitrary code target in the same process. Depending on the attack scenario, the BTI gadget is the only piece of code that is strictly required to be present in the victim. Ideally, it just consists of two instructions: one that moves the secret into a register and an indirect control-flow transfer. In order to maximize the speculative execution window, the target of the indirect control-flow transfer should be retrieved from uncached memory. An archetype of an ideal BTI gadget is a virtual function call in C++, with the secret value being an argument to such a function call. In the System V x86_64 calling convention, the first six parameters of a function are passed in registers. Further, the typical implementation of a virtual function call uses indirect direction through a vtable to resolve the binding at runtime. Since the vtable is stored in memory, the target of the call needs to be loaded, which can cause a speculation window of up to a few hundred (~200) cycles if the vtable has been evicted from the cache prior to the call. We can reasonably assume that this will happen in practice if objects are created by an early initialisation phase and used (potentially much) later in response to external events. Similarly, calls to functions in dynamically-loaded ELF (Executable and Linkable Format) libraries also employ an indirect jump, using a pointer from the Global Offset Table (GOT) to facilitate dynamic symbol resolution. Arguments in such calls may contain sensitive information which can be compromised by an attacker using these jumps as BTI gadgets.

**SMoTher Gadget.** A SMoTher gadget is the receiving end of a BTI gadget. Depending on the attack scenario, it is either already part of the victim, or can be supplied via an additional attack vector. It starts with an instruction that compares the register to a known value. The known value can either be a known immediate in the code, or, more powerfully, an attacker-controlled value specified via an additional attack vector. The next instruction needs to be a conditional control flow transfer based on this comparison leading to SMoTher-differentiable sequences. To maximize the chances of SMoTher-differentiability, the instruction sequences should each have a distinct port fingerprint such that they can be clearly distinguished from one another. This depends on the layout of the execution engine: on Intel Skylake, a prime example would be one branch with a sequence of AES instructions (only port 0) and another branch with a sequence of MDS instructions, predominantly limited to port five. Besides, the instructions should ideally not load from or store to memory, as potential cache misses introduce noise. Further, the more generic the instructions in the sequence are, the more likely it is that their execution unit does not require a warm-up phase during which execution is slow, again introducing noise.

5.1 Ranking SMoTher-gadgets

The instruction sequences we consider consist of basic blocks that start at the respective branch targets. To identify instruction sequences that are ideal for SMoTher and compare them against one another, we need to measure their suitability for SMoTher. The primary criterion is that the compare instruction operand has to match the register that is loaded with the secret in the BTI gadget. Further, we evaluate the instruction sequence at the branch target
and fall-through by quantifying three properties: (i) the port utilization difference of the two branch targets \( (r_p) \), (ii) the difference of the two branch targets in terms of the length of the branches \( (r_l) \), and (iii) the amount of memory operations in both branches \( (r_m) \).

To compare instruction sequences based on these properties, we combine them using the rank product \( RP(g) = (|\prod_{i=1}^k r_{g_i}|)^{1/k} \) for our \( k = 3 \) properties.

To compare the port utilization, we first use Intel’s Architecture Code Analyzer (IACA) to obtain a port fingerprint \( P \) for a given instruction sequence. The port fingerprint is a summary that lists the total number of cycles spent on every port for a given instruction sequence \( P = p_0 \ldots p_7 \). IACA internally uses a microarchitecture-specific model of the processor to compute the cycles, taking out-of-order execution into account. It also models the divider pipe on Skylake, allowing port zero, which handles the complex div instruction, to be ready for the next\( \text{div} \) in the next cycle, while the \( \text{div} \) is still being executed. As it cannot know better, IACA assumes all\( \text{CPU} \) resources to be fully available prior to execution of the sequence. An open-source alternative to IACA, OSA\( \text{C} \) [25] also supports AMD processors.

To compare two port fingerprints \( P \) and \( Q \), we subtract them and then calculate the utilization difference as the sum over the vector: \( r_p = \sum_{i=0}^{7} (p_i - q_i) \). The larger \( r_p \), the higher the difference in port utilization of the two instruction sequences. The utilization difference will be high for long instruction sequences that do not share a port. Such instruction sequences lend themselves well to SMT\( \text{her} \).

While a ranking based on the port utilization difference already captures the most important aspect, it has one drawback: gadgets with the complex div instruction are ranked high, whereas we prefer sequences of equal length for the timing. Therefore, we also include the inverse of the length difference \( r_l = \text{abs}(l_1 - l_2) \) between the sequences of a gadget in the ranking.

Finally, we also take the potential noise into account that can be caused by memory operations. On our targeted Skylake processors, the ports 2, 3, 4 and 7 are used for scheduling these. We include the inverse of the sum, \( r_m \), of the cycles spent on these ports in both branches as an additional ranking for the gadget. The final rank of a gadget \( g_i \) is given by \( RP(g_i) = (r_p \cdot (\text{max}(r_l) - r_l) \cdot (\text{max}(r_m) - r_m))^{1/3} \).

### 5.2 Finding Gadgets

We develop a tool to aid gadget discovery based on the popular distorm3 disassembler and Intel’s Architecture Code Analyzer, and use it to analyze a number of common system libraries that are likely to be linked to a victim executable. For the analysis we only consider gadgets with a branch length between 3 and 70 instructions, with 3 instructions being a reasonably low bound for smothering and 70 instructions being an upper bound for speculative execution. Our search looks for valid instruction sequences starting at every offset in the binary. Therefore, it would detect any SMo\( \text{ther} \)-gadget resulting from an unintended sequences of bytes (starting from the middle of an intended instruction) which might decode to valid instructions. We show the results in Table 3, the libraries analyzed are taken from a regular Ubuntu 18.04 LTS installation. We focus on SMo\( \text{ther} \)-gadgets that compare against the registers used in the x86_64 calling convention and either use the value in the register directly, or use it as a pointer and compare to a value pointed to in memory. The rationale behind this is that BTI gadgets are typically indirect calls that pass a secret, such as a cryptographic key, as a parameter. The results show that we can find enough SMo\( \text{ther} \)-gadgets even in a single common library such as glibc alone. Note that this method applies irrespective of whether the library is loaded at runtime or is statically linked into the victim’s binary. However, none of the gadgets found were formed from instructions decoded from unintended byte sequences.

One under-approximating limitation of our gadget search algorithm is that it assumes that gadgets start from the latest flag-setting instruction before the jump. Suppose a sequence in the victim’s code is shl 8, rax; test 1, rax; jz \#add. Our tool will find test 1, rax; jz \#add; as a SMo\( \text{ther} \) gadget which leaks the least significant bit (LSB) of rax. However, the instructions preceding this might perform computations which cause the gadget to leak different information. The entire sequence is a different SMo\( \text{ther} \) gadget which leaks the 9-th least significant bit of rax. The space of usable SMo\( \text{ther} \)-gadgets exceeds the ones we have found, and depend on the particular victim’s code.

### 6 REAL WORLD ATTACK

We demonstrate real-world attacks on OpenSSH and OpenSSL, two commonly used programs handling sensitive secrets that have been extensively hardened against regular and side-channel attacks.

#### 6.1 OpenSSH attack

OpenSSH is widely used to securely and privately connect to servers over untrusted networks. The confidentiality of the server’s private key is essential to the security of the overall system. Leaking the private server key allows an attacker to impersonate the server, acting as a man in the middle. In the OpenSSH attack, we find a BTI...

| Library | RDI | RSI | RDX | RCX | R8 | R9 |
|---------|-----|-----|-----|-----|----|----|
| glibc 2.23 | 1155 | 1502 | 3864 | 4256 | 568 | 615 |
| stdcc++ 6.0 | 1040 | 932 | 257 | 1029 | 135 | 29 |
| ld 2.23 | 189 | 400 | 869 | 1399 | 97 | 73 |
| pthread 2.23 | 209 | 65 | 98 | 276 | 58 | 14 |
| z 1.2.11 | 105 | 130 | 412 | 359 | 41 | 31 |
| crypto 1.1 | 46 | 47 | 29 | 110 | 6 | 0 |
| ssl 1.1 | 23 | 56 | 70 | 82 | 25 | 8 |

Table 3: SMo\( \text{ther} \)-gadgets we found in common system libraries, for the registers used to pass arguments in the System V x86_64 calling convention. First line: number of SMo\( \text{ther} \)-gadgets that use the value in the register, second line: number of gadgets that use its pointee.
which clears regions of memory. The function is extensively used
This invocation is present in the code path handling new connec-
in that it compares the value of a memory location pointed to
SMoTher gadget differs slightly from that described in Section 4.2
ure 5b (see Appendix C for the full assembly listing). Our chosen
An abridged version of the SMoTher gadget is shown in Fig-
by a register, not the value of the register itself. The target and
fall-through path differ in utilization of execution ports 0156. This
gadget is taken from glibc and demonstrates the availability of
SMoTher gadgets in commonly linked libraries. The attacker times
a sequence of add instructions with register operands (port 0156)
shown in Figure 5a to specifically target the same ports.
We ran our attack on a slightly-modified sshd server. The ssh
server is modified to setup relevant performance counters to be
used for statistical and monitoring purposes. These counter values
are ignored by the actual attack. The other modification is to syn-
chronize the attacker with the BTI gadget (as in Section 4.3). For
other targets (i.e., OpenSSL), we have investigated alternate syn-
chronization mechanisms that do not require victim modification
and have good results. The server was compiled using the default
options for Linux on x86_64.
In the PoC of the attack, an orchestrator process randomly sets
the bit to be leaked before launching the server and attacker on
colocated logical cores. The attacker process is responsible for “poi-
soning” the BTB to cause mis-speculation on the victim process
handling the incoming ssh connection. Prior to BTI, the attacker
also performs a series of cache accesses that result in the eviction
of the server’s cache line containing the function pointer ssh_bzero.
This forces the victim’s indirect call instruction to miss in the cache
and speculate for a few cycles, increasing the BTI success rate. The attacker
process is otherwise identical to the victim and follows the
same code path, increasing the probability of the attacker having
the same branching history as the victim at the call site, thereby
increasing the success rate of BTI. The orchestrator launches an
ssh client on a separate physical core to connect to the server and
trigger the creation of the victim and attacker processes. Victim
and attacker process execute and the attacker is able to collect a
SMoTher-timing sample correlated to the value the LSB in byte 1
of the host private key.
The attack can be extended in two ways. First, we can pair our
BTI gadget with other SMoTher gadgets in the victim, enabling
us to leak other bits of the host private key. Second, we can find
other occurrences of the explicit_bzero BTI gadget (or other BTI
gadgets) where different secrets are held in registers or in memory.
In the explicit_bzero BTI gadget, we found that the value of
the register r12 equals the value of rdi, both pointing to the host
key in memory at the point of attack. Therefore, we are able to
use three other SMoTher-gadgets which dereference r12. These
gadgets allow us to leak extra bits from the host key, specifically the

(a) Attacker-timed code  (b) Victim SMoTher gadget (glibc)  (c) Victim BTI gadget (OpenSSH)

Figure 5: Gadgets from real-world libraries used in our SMoTherSpectre exploit for leaking the $t$th least significant bit of rdx’s pointee
4th LSB in byte 13, the 4th LSB in byte 14 and the 5th LSB in byte 56. The corresponding assembly listings are shown in Appendix C.2.

Additionally, we can also find other BTI gadgets, or invocations of explicit_bzero with different secrets. Other secrets erased by this function include contents of the /etc/shadow file and client passwords in cleartext received during login attempts.

6.2 OpenSSL attack

For OpenSSL, we target a BTI gadget in the libcrypto library (version 1.1.1b, dated 26-Feb-2019) which is widely used for performing cryptographic functions and a SMoTheir gadget from glibc version 2.27.

Over the years, considerable effort was devoted to thwarting potential attackers and to protect OpenSSL from side-channel attacks, primarily by removing data-dependent memory-access or control flow. Our attack, however, targets BTI gadgets (indirect jumps or calls) that are found in code used to choose between encryption modes, allowing for multiple modes of operation (such as ECB, CBC, GCM) with the same block cipher. OpenSSL uses a context variable that stores function pointers for encryption/decryption. These pointers are set during the initialization phase depending on the user-specified cipher mode.

As a result, cryptographic applications using libcrypto execute an indirect call (the BTI gadget) during every block encryption or decryption. Such gadgets are the result of commonly used coding practices, and do not directly perform any data-dependent actions based on the secret value. As in the OpenSSH attack, the use of function pointers leads to indirect calls in the compiled binary. While security was the motivating factor for OpenSSH, OpenSSL uses function pointers to support polymorphic-like behavior, enabling our transient execution attack.

Our BTI gadget is contained in EVP_EncryptUpdate, and is shown in Figure 6c. The third argument (in) contains a pointer to the plaintext to be encrypted (and is therefore a secret). In accordance with the System V calling convention, this pointer is stored in register rdx prior to the call. The secret in our chosen SMoTheir gadget is the 3rd LSB in byte 1 of the plaintext, referenced through rdx. An abridged version of the SMoTheir gadget is shown in Figure 6b (see Appendix B for the full assembly listing).

In our attack, we model a victim that encrypts text using OpenSSL’s EnVeloP (EVP) API. After performing the necessary initializations, it performs a series of encryptions using calls to EVP_EncryptUpdate. We have also instrumented the victim to setup relevant performance counters which are only used for statistical and monitoring purposes and are not used in the attack. The victim library does not contain any code to help the attacker synchronize with the execution of the BTI gadget.

The attacker triggers the encryptions on the victim. It also runs code that is almost identical to the victim apart from the following differences. First, it loads the call pointer with the location of the SMoTheir gadget on the victim to trigger BTI on the victim process. Second, it replaces the code at the target location by a delay sequence and the SMoTheir timing. The delay sequence consists of a series of dependent instructions that allows the attacker to delay for a controlled number of cycles, synchronizing with the victim’s SMoTheir gadget, before measuring the timing sample. Otherwise, the attacker runs code that mimics the victim: it performs the same call to the encryption function where it follows the same sequence of checks and jumps. It also runs in a loop performing the same number of iterations, thus maximising the success of BTI. In each iteration, the attacker gets one timing measurement. Between iterations, the attacker performs a series of memory accesses designed to evict the victim’s cache line holding the pointer to the encryption function from the L1 cache to increase the BTI success rate. We observed that other usual work being performed on the core can have the same effect.

6.3 Experimental results

We run the OpenSSH attack on a quad-core, hyper-threaded Skylake CPU (i7-6700K) with the server and attacker pinned on logical cores 0 and 4 respectively (running on physical core 0). For each connection attempt to the server, the orchestrator randomly sets or resets the target bit, logs its value and the attacker measures a SMoTheirSpectre timing sample. We run the attack 10,000 times and separate the collected samples based on the value of the target bit on that particular run, yielding two sets of attacker timings corresponding to the target bit being zero or one. Finally, we run the Student’s t-test to check whether the sets are statistically distinguishable. We used this methodology on four SMoTheir-gadgets described in Section 6.1. Table 4 shows the results: the distributions are differentiable with at-least 95% confidence for each of the four gadgets. The attack does not require extremely high BTI success rate: in our samples, we observe BTI success rates ranging between 16% and 25%. The whole experiment takes about 75 seconds of real-time, of which a total of 20 seconds are spent by the orchestrator waiting for the server to be fully setup before launching the client.

We run the OpenSSL attack on an i5-6200u CPU. A run of 100,000 encryptions is performed by the victim for each value of the secret bit. The large number of encryptions is necessary to estimate the probability density function for this SMoTheir-gadget. A practical attack can confidently leak a bit with fewer encryptions. The attack takes about 950 ms of userspace time, leading to a measurement rate of more than 200,000 samples/second. The attacker succeeded in BTI with a success rate up to around 80%. We have found the time taken by the victim to reach the indirect call from the call triggering encryption entry to be highly predictable. The attacker is thus able to run the timing sequence concurrently with the victim’s SMoTheir-gadget without additional synchronization. Figure 7 shows the distribution of timestamp counter difference.

| Pointer register | Byte Offset | Bit mask | A SMoTheir timing |
|------------------|-------------|----------|-------------------|
| rdi              | 0x00       | 0x01     | 0.32% ± 0.21%     |
| r12              | 0x08       | 0x10     | 0.64% ± 0.62%     |
| r12              | 0x0d       | 0x08     | 0.66% ± 0.47%     |
| r12              | 0x0c       | 0x08     | 0.42% ± 0.33%     |

Table 4: SMoTheirSpectre results leaking the sshd private key. Four gadgets, each targeting a different key bit identified by its byte offset and bit mask, were used. We also show the mean timing difference percentage for the attacker’s SMoTheir timing, separated according to the value of the randomly-set target bit: all show a difference at 95% confidence.
.rept 8; 
   0xf5393: testq 0x400,(rdx)   if(ctx->cipher->do_cipher(ctx, out, in, inl))
   0xf5399a: je f5382
   0xf539c: mov -0xb0(rbp),rdi   *
   0xf5382: add 0x1,rax
   .endr;

(a) Attacker-timed code  (b) Victim SMoThER gadget (glibc)  (c) Victim BTI gadget (OpenSSL)

Figure 6: Gadgets from real-world libraries used in our SMoThER Spectre exploit for leaking the 3rd LSB of byte 1 of rdx’s pointee.

Figure 7: Probability density function (estimated using kernel density estimation) for the attacker’s timing running our SMoThER Spectre attack on OpenSSL, for when the victim’s secret bit is one versus zero.

measured by the attacker for the SMoThER gadget. The distributions show a significant variation, with that corresponding to the zero-secret tending towards higher values. The Student’s t-test is able to successfully distinguish between them with 95% confidence. The test reports a timing difference of 10.69% ± 6.31%.

6.4 Mitigating SMoThER Spectre

Mitigations for SMoThER Spectre can be subdivided in two categories: mitigations for SMoThER and mitigations for BTI.

SMoThER mitigations. The general idea of preventing SMoThER attacks is to ensure that two threads with different privileges (in the general sense) do not compete for the same execution port.

Currently available software SMoThER mitigations are limited. Apart from the straightforward but performance-costly possibility of disabling SMT in its entirety (up to 10-15% overhead on Intel), the OS scheduler can employ a side-channel aware strategy. For example, the OS scheduler can decide to only colocate (on threads on the same core) processes from the same user [12].

Finally, CPU-level mitigations could be deployed in the future, possibly improving both security and performance over existing mitigations. For instance, alternatives to SMT can be considered to achieve thread-level parallelism within a core. These include coarse-grained and interleaved multithreading.

BTI mitigations. Mitigations against branch target injection are also known as Spectre v2 mitigations. These include retpolines, which rewrite code to remove indirect calls [33], as well as CPU-based controls. Intel has exposed to developers a set of security controls that limit an attacker’s ability to perform BTI. While they have been applied in selected cases, they have not been widely adopted because of their overhead [7], and because in many cases, the required gadgets were simply not present [23]. Wide adoption of these mitigations may limit the SMoThER Spectre attack.

Summary. Fully mitigating the attack in either of these two categories is sufficient to stop the attack presented in this paper. However, SMoThER Spectre does not necessarily need to employ BTI: it can be generalized to use any other form of speculative control flow hijack, e.g., Return Stack Buffer (RSB) overflow [27] or speculative return address overwrite [22]. In those cases, corresponding mitigations would apply.

7 RELATED WORK

Transient Execution Attacks. Transient execution attacks exploit instructions that are executed, yet not necessarily retired and thus cover both attacks based on speculative execution as well as out-of-order execution [5].

At the beginning of 2018, two security issues exploiting speculative execution were revealed under the name “Spectre” [18, 23]. Spectre V1 (“Bounds Check Bypass”) exploits branch prediction on a conditional branch to achieve an out-of-bounds access during speculative execution: given a conditional branch that performs a bounds-check on an array, the branch predictor is trained to the in-bounds case by performing multiple executions of the corresponding code with a benign index. When the code is then executed with an out-of-bounds index, a misprediction occurs and the array access with the malicious index is performed. If the result is used in further computation such as another array access, it can be leaked through a side channel. Spectre V2 (“Branch Target Injection”) exploits branch prediction on indirect control-flow transfers. To this end the attacker first trains the branch predictor for a given address to transfer control to an address of the attacker’s choosing. The predictor will then use the branch history created by the attacker for a spatially or temporally co-located victim. Again, a cache side-channel can be used to leak data of the attackers choosing in the following. The return stack buffer, which is used for return statements in a similar fashion as the branch history is used for indirect jumps has also been leveraged as a speculative execution
Accesses to cached locations will be faster, whereas accesses to as Netspectre [29] demonstrates they also work remotely. While "Rogue System Register Read". The more recent Foreshadow [34] is that the attacker measures her own operation in contrast to the addresses used for probing: it will be low for addresses touched by cache with known attacker-controlled addresses. One then waits for the cache by executing a victim function and then measures how the cache by executing a victim function and then measures how.

The return address on the stack has also been the target of other work, showing that through load-to-store forwarding it can be speculatively overwritten, leading to a speculative execution sibling of the classic stack buffer overflow [22].

Meltdown [26] ("Rogue Data Cache Load"), which was also revealed in early 2018 exploits out-of-order execution: a memory load instruction immediately after a high latency instruction might fetch data into the cache even if it is not permitted to access the actual memory location. The reason is that on certain CPUs, the corresponding permission check is not on the critical path for the data fetch and the exception is only triggered after the data fetch. On such CPUs this allows reading arbitrary kernel memory from userspace. Similarly, also privileged system register can be read ("Rogue System Register Read"). The more recent Foreshadow [34] attacks a similar phenomenon, "L1 Terminal Fault" in Intel nomenclature. If an instruction accesses a virtual address that is not in the translation lookaside buffer (TLB) and the corresponding page table entry’s (PTE) present bit is not set, this is referred to as a "terminal fault". During out-of-order execution, the processor computes a physical address from the PTE, which is used for a lookup in the L1 data cache. Until the instruction retires a page fault is raised, cached data is forwarded to dependent instructions, which can be used in an attack. This bypasses various access checks, including SGX protection, extended page table address translation and system management mode (SMM) checks, thus affecting virtualization and SGX enclaves (enclave data is not encrypted in L1D). Also related to out-of-order execution is the speculative store bypass [3, 20]: for a code sequence of a dependent store and a load instruction, the load instruction, if executed out-of-order before the store might retrieve stale data from memory that can be used in a side channel. This happens in cases where the CPU cannot detect the dependency in the code sequence.

Transient execution attacks are not only a local security issue that requires a victim device to execute attacker-controlled code. As Netspectre [29] demonstrates they also work remotely. While being less effective, they are still powerful enough to break, for example, address space layout randomization.

Cache Side Channels. Cache side channels leverage timing differences in accesses to different tiers of the memory hierarchy. Accesses to cached locations will be faster, whereas accesses to uncached locations will be slower, as the data needs to be fetched from main memory. This principle applies to both data and instructions: Execution of code whose instructions are not cached will take longer than execution of cached code.

To use an evict-and-time cache side channel, one first primes the cache by executing a victim function and then measures how long the function takes to execute – this is the baseline run. One can now compare this baseline against further executions of the function, with different cache sets evicted. If the time the function takes to execute is slower than the baseline, the victim function depends on the evicted cache set.

To use a prime-and-probe cache side channel, one first primes the cache with known attacker-controlled addresses. One then waits for the victim code to run. Afterwards, one measures the access time to addresses used for probing: it will be low for addresses touched by the victim code and high for others. The difference to evict-and-time is that the attacker measures her own operation in contrast to the execution of victim code. Both evict-and-time and prime-and-probe have been extensively used to attack AES implementations [28, 32].

Another technique that became popular with attacks leveraging a shared last-level cache (LLC) is flush-and-reload. It requires an instruction that allows an attacker to flush a certain cache line, such as c1flush on x86_64. In a corresponding attack, the attacker first flushes a cache line and then waits for the victim code to execute. Afterwards the attacker times the access to the address, which will be fast if the victim accessed (reloaded) it and slow otherwise. Flush-and-reload is similar to prime-and-probe, but much more fine-grained as individual cache lines can be targeted. It has been used to leak information from the LLC, which is typically shared among multiple CPU cores [36]. Related to flush-and-reload, flush-and-flush [16] is based on the observation, that c1flush will take less time to execute when it is run on a location that is not cached. The advantage over flush-and-reload is that no actual access that would pull data into the cache is performed, making the attack stealthier.

Finally, prime-and-abort leverages Intel’s transactional memory mechanism to detect when a cache set has been evicted without the need to probe the cache [8]. In contrast to all previous cache side channels, it does not need to time an operation. Transactional memory operations require transactional data to be buffered in the cache which has limited space. A transaction set up by the attacker will abort if the victim accesses a critical address.

Other Side Channels. Mitigations against cache-based side channels have led researchers to explore other shared resources as well. TLBleed [14] shows how the TLB can be used as a side channel to leak a cryptographic key. Aforementioned Netspectre-AVLX [29] uses a side channel based on AVX instructions. This side channel exploits the fact that the execution unit processing those instructions employs aggressive power saving. When such units have not been used for a long time, they execute much slower. In particular, execution-unit-sharing-based side channels in the SMT settings have been studied as early as in 2006: Wang and Lee [35] demonstrate a multiply-based covert channel making use of contention on execution units. Aciicmez and Seifert [1] extend this work by analyzing its applicability as a side channel. Anders Fogh [11] proposes a generalized result by analyzing contention results of the cross product of 12 curated instructions. Finally, Portsmash [2], concurrently and independently demonstrates how port contention can be used to leak sensitive cryptographic material from OpenSSL. Portsmash relies on a known vulnerable implementation of OpenSSL, and therefore does not require any mitigation beyond avoiding vulnerable code patterns. In contrast, SMOTHERSPECTRE does not require a secret-dependent control flow by combining port contention with BTI, and thereby showing broader applicability of the port contention side channel. Finally, in contrast with all previous works, this work provides a characterization of this side channel, including an analysis for low number of victim instructions.

8 CONCLUSION
We further our understanding of possible attacks in the space of speculative execution. This is crucial to design suitable defenses and to apply them to the right systems. In particular, we show
that Branch Target Injection attacks against applications that do not load attacker-provided code are feasible, by crafting an exploit for the OpenSSH server and encryption using OpenSSL. To this end, we present a precise characterisation of port contention, the non-cache-based side channel we use for the attack, and develop a tool to help us find suitable gadgets in existing code. We will open-source our proof of concept implementation, gadget finder, as well as the data of our measurements to enable others to study this interesting side channel. As a consequence, it is now clear that in SMT environments defenses solely relying on mitigating cache side channels, or solely relying on reverting microarchitectural state after speculative execution, are insufficient.

In the immediate future, implementing existing BTI mitigations is sufficient to prevent SMoTheR-SPECTRE. Future work may mitigate such attacks with lower performance overhead and better security guarantees, for instance through side-channel resistant ways of designing thread-level parallelism in upcoming CPUs.

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A GADGETS LEAKING 21 BITS OF RAX

The following table lists parts of SMoTheR-gadgets which can be used to leak 21 bits of information from rax. We also show which library the gadget was found in.
### B  OPENSSL ATTACK GADGETS

#### B.1  SMoTHER gadget

The following gadget leaks the 3rd LSB from the byte at offset 1 from the pointer in rdx.

| Address  | Comparison Instruction | Library          |
|----------|------------------------|------------------|
| f5393:   | testq 0x400, (rdx)     | glibc            |
| f539a:   | je f5382               |                  |
| f539c:   | mov -0xb0(rbp), rdi   |                  |
| f53a3:   | mov -0xf0(rbp), edx   |                  |
| f53a9:   | mov (rdi, rax, 8), rax |                  |
| f53ad:   | test edx, edx         |                  |
| f53af:   | mov rax, 0x50(rbx)     |                  |
| ...      |                        |                  |
| f5382:   | add 0x1, rax           |                  |
| f5386:   | add 0x20, rdx          |                  |
| f538a:   | cmp rax, -0x100(rbp)   |                  |
| ...      |                        |                  |

#### C  OPENSSH ATTACK GADGETS

#### C.1  SMoTHER gadget with rdi pointer

The following gadget leaks the LSB from the byte at offset 1 from the pointer in rdi.

| Address  | Comparison Instruction | Library          |
|----------|------------------------|------------------|
| 6f8dc:   | testl 0x100, (rdi)     |                  |
| 6f8e2:   | je 6f8ef               |                  |
| 6f8e4:   | mov 0x10(rbx), rax     |                  |
| 6f8e8:   | sub 0x8(rbx), rax      |                  |
| 6f8ec:   | sub rax, rsi           |                  |
| 6f8ef:   | mov rbx, rdi           |                  |
| 6f8f2:   | mov ecx, 0xc(rsp)      |                  |
| 6f8f6:   | mov edx, 0x8(rsp)      |                  |
| 6f8fa:   | mov rsi, (rsp)         |                  |
| ...      |                        |                  |

#### C.2  SMoTHER gadgets with r12 pointer

The following gadget leaks the 5th LSB from the byte at offset 56 from the pointer in r12.

| Address  | Comparison Instruction | Library          |
|----------|------------------------|------------------|
| e8577:   | testb 0x10, 0x38(r12)  |                  |
| e857d:   | je e8608               |                  |
| e8583:   | sub 0x8, rsi           |                  |
| e8587:   | push rbx               |                  |
| e8588:   | pushq 0x0              |                  |
| e858a:   | pushq 0x0              |                  |
| e858c:   | mov edx, r8d           |                  |
| e858f:   | mov edx, r9d           |                  |
| e8592:   | mov r10d, ecx          |                  |
| e8595:   | sub r10d, r8d          |                  |
| e8598:   | mov r13, rsi           |                  |
| e859b:   | mov r12, rdi           |                  |
| ...      |                        |                  |
| e8608:   | sub 0x8, rsi           |                  |
| e860c:   | push rbx               |                  |
| e860d:   | push r14               |                  |
| e860f:   | push r15               |                  |
| ...      |                        |                  |

The following gadget leaks the 4th LSB from the byte at offset 12 from the pointer in r12.

| Address  | Comparison Instruction | Library          |
|----------|------------------------|------------------|
| 5220e:   | testb 0x8, 0xd(r12)    |                  |
| 52214:   | je 52221               |                  |
| 52216:   | xor edx, edx           |                  |
| 52218:   | xor esi, esi           |                  |
| 5221a:   | xor edi, edi           |                  |
| ...      |                        |                  |
| 52221:   | mov r13, rcx           |                  |
| 52224:   | add 0x3, r13           |                  |
| 52228:   | sar 0x2, rcx           |                  |
| 5222c:   | cmp 0x6, r13           |                  |
| ...      |                        |                  |

The following gadget leaks the 4th LSB from the byte at offset 13 from the pointer in r12.

| Address  | Comparison Instruction | Library          |
|----------|------------------------|------------------|
| 529a2:   | testb 0x8, 0xc(r12)    |                  |
| 529a8:   | je 523da               |                  |
| 529ae:   | mov -0x100(rbp), rcx   |                  |
| 529b5:   | lea 0xc(rcx), rdx      |                  |
| 529b9:   | cmp rax, rdx           |                  |
| ...      |                        |                  |
| 523da:   | mov -0xf8(rbp), r13d   |                  |
| 523e1:   | mov (rax), edx         |                  |
| 523e3:   | add -0xe0(rbp), r13d   |                  |
| ...      |                        |                  |

#### D  RESPONSIBLE DISCLOSURE

The attacks presented in this paper were disclosed to Intel, OpenSSL and AMD in late 2018.
