**DIALED**: Data Integrity Attestation for Low-end Embedded Devices

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**Abstract**—Verifying integrity of software execution in low-end microcontroller units (MCUs) is a well-known open problem. The central challenge is how to securely detect software exploits with minimal overhead, since these MCUs are designed for low cost, low energy and small size. Some recent work yielded inexpensive hardware/software co-designs for remotely verifying code and execution integrity. In particular, a means of detecting unauthorized code modifications and control-flow attacks were proposed, referred to as Remote Attestation (RA) and Control-Flow Attestation (CFA), respectively. Despite this progress, detection of data-only attacks remains elusive. Such attacks exploit software vulnerabilities to corrupt intermediate computation results stored in data memory, changing neither the program code nor its control flow. Motivated by lack of any current techniques (for low-end MCUs) that detect these attacks, in this paper we propose, implement and evaluate DIALED, the first Data-Flow Attestation (DFA) technique applicable to the most resource-constrained embedded devices (e.g., TI MSP430). DIALED works in tandem with a companion CFA scheme to detect all (currently known) types of runtime software exploits at fairly low cost.

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**I. INTRODUCTION**

Embedded systems are growing in number and variety in recent years, rapidly becoming ubiquitous in many aspects of modern society. Some are ultra-cheap and specialized, built atop low-energy, low-cost, and tiny MCUs, e.g., TI MSP430 and AVR ATMega32. Despite being extremely resource-constrained, these MCUs often perform safety-critical tasks that involve sensing and/or actuation. Hence, their security is very important.

Securing low-end MCUs is very challenging, since they often lack any security-relevant hardware features. At the lowest end of the spectrum, devices have no MMUs or MPUs, and thus have no means to support an OS or even a microkernel. Hence, sophisticated malware prevention and detection techniques that work on smartphones, laptops, desktops, and servers are inapplicable. To address this problem, a number of architectures [12], [8], [18], [3], [16], [20], [14], [19], [9] were proposed to support rudimentary security services on low-end MCUs. One prominent research direction involves so-called hybrid (hardware/software co-design) architectures that offer strong security guarantees at minimal hardware cost.

In that vein, architectures for Remote Attestation (RA) [12], [8], [3], Proofs of Execution (PoX) [18], and Control-Flow Attestation [9] are of particular interest. RA is an interaction between a trusted and more powerful entity, called a Verifier (Vrf) and a potentially compromised remote low-end device, called a Prover (Prv). It allows Vrf to securely measure Prv’s memory contents, enabling detection of malware that modifies code installed on Prv. PoX augments RA by providing Vrf with a proof that the attested code was executed and that any claimed outputs (e.g., sensed values) were indeed produced by executing the expected code. Finally, CFA detects control-flow attacks, whereby benign code on Prv contains unknown bugs (e.g., buffer overflows caused by lack of array bound checks) that can be exploited to hijack the program’s control-flow, i.e., the order of instruction execution. In summary, CFA provides Vrf with a proof that benign code was executed in a particular valid or expected order.

Despite these advances, detection of data-only attacks remains elusive. Similar to control-flow attacks, data-only attacks exploit vulnerabilities in benign code to corrupt intermediate values in data-memory. It is well-known [22], [15] that data-only attacks need not alter the code or its control-flow in order to corrupt data. Without a way to detect data-only attacks (as well as code and control-flow modifications) results of Prv’s remote computation cannot be trusted.

Very recently, a novel technique supporting both CFA and DFA, called OAT [21], was proposed. However, it implements DFA by relying on trusted hardware support from ARM TrustZone, which is only available on higher-end platforms (e.g., smartphones, Raspberry Pi, and similar) and is not affordable to low-end, low-energy MCUs. In addition, OAT’s security relies on the application programmer’s ability to correctly annotate all critical variables in the code to be attested. This is a strong assumption, since most control-flow and data-only exploits are caused by implementation bugs introduced by the very same application programmer. Naturally, it would be beneficial for this assumption to be avoided.

In this paper, we focus on security against data-only attacks on low-end MCUs and propose DIALED: Data Integrity in Attestation for Low-end Embedded Devices. DIALED’s only hardware requirement is that already provided (at relatively low-cost) by the PoX architecture APEX [18]. DIALED uses APEX to securely log and authenticate any data inputs used by the program. This authenticated log allows Vrf to reconstruct the entire data-flow of the program’s execution, thus enabling detection of any data-corruption attacks via abstract execution of the attested program.

Similar to OAT, DIALED is implemented alongside Tiny-CFA [9], a low-cost CFA technique. This composition enables, for the first time, detection of both control-flow and data-only attacks for low-end MCUs. Notably, DIALED does not rely on code annotation; thus, its security neither requires, nor depends on, any human intervention. In the rest of this paper, we describe DIALED’s design and analyze its security. We also report on the implementation of DIALED along with Tiny-CFA on the TI MSP430 MCU and demonstrate its cost-effectiveness by providing both CFA and DFA for three applications.

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**II. BACKGROUND & PROBLEM STATEMENT**

This section overviews targeted devices and defines the problem setting.

**A. Scope of Low-End MCUs**

This paper focuses on tiny CPS/IoT sensors and actuators, or hybrids thereof. These are some of the smallest and weakest devices based on low-power single-core MCUs with small program and data...
memory (e.g., aforementioned Atmel AVR ATMega and TI MSP430), with 8- and 16-bit CPUs running at 1-16MHz, with ≈ 64 KBytes of addressable memory. SRAM is used as data memory, normally ranging between 4 and 16KBytes, while the rest of the address space is available for program memory. Such devices usually run software atop “bare metal”, execute instructions in place (physically from program memory), and lack any memory management unit (MMU) to support virtual memory.

B. Control-Flow vs. Data-Only Attacks

Both control-flow and data-only attacks violate program execution integrity without modifying the actual executable, by taking advantage of implementation bugs, e.g., lack of array bound checks. Such vulnerabilities are quite common in memory-unsafe languages, such as C, C++, and Assembly, which are widely used to program MCUs.

```
1 int dose = 0;
2 void injectMedicine(){
3   int copy_of_commands[5];
4   if (dose = 10){ /* safety check preventing overdose */
5      P3OUT = 0x1;
6      delay(dose*time_per_dose.unit);
7   }
8   P3OUT = 0x0;
9   }
10
11 void parseCommands(int *recv_commands, int length){
12   int copy_of_commands[5];
13   memcpy(copy_of_commands, recv_commands, length);
14   dose = processCommands(copy_of_commands);
15   return;
16 }
```

Fig. 1. Embedded application vulnerable to a control-flow attack [9].

Control-flow attacks change the order of instructions execution thus changing program behavior, escalating privilege, and/or bypassing safety checks. Consider the example in Figure 1 (taken from [9]). In this embedded application, the MCU is connected through the general purpose input/output (GPIO) port P3OUT (lines 5 and 8) to an actuator that injects a certain dose of medicine, determined in software, according to commands received from the network, e.g., from a remote physician.

The function injectMedicine injects appropriate dosage given by the variable dose, by triggering action for period of time proportional to the value of dose. To guarantee a safe dosage, the if statement (line 4) assures that the maximum injected dosage is 9, thus preventing the patient from over-dosing due to errors. The function parseCommands (line 11) makes a copy of received commands and processes them to determine the appropriate dosage. However, this function can be abused by a control-flow attack at line 13. Specifically, because copy_of_commands has a fixed length of 5, an input array of size more than 5 causes a buffer overflow corrupting the data in stack, including the return address of parseCommands. In particular, the return address can be overwritten with the value of recv_commands[5]. By setting the content of parseCommands[5] to be the address of line 5, such an attack causes the control flow to jump directly to line 5, skipping the safety check at line 4, and potentially overdosing the patient.

As mentioned earlier, CFA securely logs all control-flow deviations and (upon request) provides an authenticated copy of this log to Vrf, enabling detection of the aforementioned attack. We overview a concrete CFA architecture in Section II-C. However, CFA cannot detect data-only attacks that do not change the control-flow. Figure 2 presents a second implementation attempt, vulnerable to data-only attacks. To see this vulnerability, note that P3OUT register controls multiple physical ports, each associated with one bit in P3OUT register, e.g.:

- Setting P3OUT = 0x0000000 = 0x0 turns all physical ports off
- Setting P3OUT = 0x000001 = 0x1 turns on 1st physical port
- Setting P3OUT = 0x0000010 = 0x2 turns on 2nd physical port
- Setting P3OUT = 0x0000011 = 0x3 turns on both 1st and 2nd physical ports, etc.

In order to trigger actuation through the proper port (Port 1 in this example), this code needs to set P3OUT = 0x1. This is configured in the global variable set, at line 1 of Figure 2. The value of set is later used to trigger actuation at line 8. The code also allows settings to be updated at an arbitrary position defined by the input parameter index. Since settings has a fixed length of 8, a malicious input with index = 8 would overflow this buffer causing set to be overwritten with the value of new setting. An input new setting = 0 with index = 9 would overwrite set = 0. Later, at line 8, when set is used to trigger actuation of port 1, it will instead have no actuation effect (since it is now 0). Consequently, the medicine will not be injected. It is important to note that this attack does not change the program control flow, but just corrupts data. It therefore can not be detected by CFA alone.

```
1 int set = 0x1; // configured to cause actuation on Port 1
2 int settings[8]; // default settings produce dose = 5ul
3
4 void injectMedicinePort1(int new_setting, int index){
5   settings[index] = new_setting;
6   if (dose > 10){ /* safety check preventing overdose */
7      P3OUT = set;
8      delay(dose*time_per_dose.unit);
9   }
10   P3OUT = 0x0;
11   return;
12 }
```

Fig. 2. Embedded application vulnerable to a data-flow attack.

C. Prior Work: CFA

In recent years several CFA techniques have been proposed [2], [11], [10], [23], [21]. We focus on Tiny-CFA, the only CFA for low-end devices targeted in this work. Tiny-CFA is constructed atop another recently proposed technique – APEX formally verified architecture [18] that implements the so-called Proof-of-Execution (PoX) primitive. Tiny-CFA imposes no additional hardware requirements, beyond those imposed by APEX. The PoX primitive allows P nutriture to prove to Vrf cryptographically binding the following guarantees:

1) The proper/expected code is loaded at a particular location in P nutriture’s program memory, referred to as Executable Range (ER).

2) This proper/expected code was executed in its entirety: from its first instruction = its legal entry point, until its last instruction = its legal exit.

3) All outputs are authentic and were indeed produced by this execution. The outputs are written to a specific memory location, referred to as Output Range (OR).

Sizes and locations of ER and OR are configurable, which enables PoX for arbitrary code and arbitrary outputs. APEX is formally verified to guarantee secure PoX even in case of a full software compromise of the underlying MCU. APEX also prevents any external data memory modifications that could attempt to tamper with ER’s state while the code in ER is running (e.g., via interrupts or DMA).

Tiny-CFA implements CFA atop APEX by instrumenting the executable with instructions that log the control flow to APEX-authenticated OR region. Specifically, given an executable, Tiny-CFA instruments all control flow-altering instructions (e.g., jumps, branches, function calls, and returns) by logging the destination address of each such instruction to the OR region. Tiny-CFA also assures that the log in OR cannot be modified. This way, given
APEX formal guarantees, $\forall rf$ securely learns the exact control flow of program execution on a remote $Prv$.

DIALED also uses code instrumentation and augments Tiny-CFA with the detection of data-only attacks. DIALED’s core idea is to log (and send to $\forall rf$) all the inputs of the program during execution along with its control flow, which enables $\forall rf$ to emulate the entire execution of the attested program, allowing it to detect both control-flow and data-flow attacks. DIALED is detailed in the next section.

III. DIALED DESIGN

Figure 3 shows the components of DIALED: it is implemented alongside Tiny-CFA (itself based on APEX) to provide both CFA and DFA. The executable is separately instrumented by both Tiny-CFA and DIALED. APEX provides a proof of the execution of the instrumented executable, serving as an authenticator for its output: a log containing the executable’s control flow and its data inputs.

A. Overview

To detect data-only attacks, DIALED uses a novel input detection method via secure instrumentation of the executable. This instrumentation guarantees that all relevant data is logged during program execution; this is in addition to the control-flow log produced by Tiny-CFA. The underlying PoX primitive provides $\forall rf$ with a proof that this output (containing all relevant data and the control-flow path) was indeed produced by the execution of the expected (instrumented) code. In doing so, DIALED provides $\forall rf$ with all information needed to abstractly execute this program locally and detect any code, control flow, or data compromises. The core feature of DIALED is detection and secure logging of every external input received during program execution, including input from peripherals, the network, GPIO, as well as data fetches from memory locations outside the executable’s own state.

Similar to OAT [21], the goal is to attest embedded operations, i.e., finite and self-contained safety-critical functions called by the program’s main loop. Examples include sensing and actuation tasks triggered by commands received through the network, as in Section II-B. Since embedded operations typically have well defined and reasonably small number of data inputs, DIALED can efficiently save all inputs to an append-only log – Input Log (I-Log). DIALED instrumentation assures that all data inputs are appended to I-Log.

Definition 1 (Data Inputs). Any value read from any memory location outside of the attested program’s current stack. The program’s current stack is the region located within the current stack pointer value (top of the stack) and the value of the stack pointer when the attested program was first called (based of the program’s stack). It includes all local variables.

According to this definition, read instructions that move/copy data from peripherals, network or GPIO are considered as Data Inputs and written to I-Log, since these involve reads from memory outside of the program’s stack. But reads that occur during regular computation, e.g., instructions which compute on local variables are not written to I-Log, as they are not inputs. This approach makes the size of I-Log relatively small, which is confirmed by the real-world embedded operations considered in our evaluation in Section V.

Recall that Tiny-CFA instruments the executable to produce a Control-Flow Log (CF-Log). In DIALED, both CF-Log and I-Log are written to APEX-designated output region $OR$. Hence, $\forall rf$ is assured of the integrity of these logs. In addition, given the attestation guarantee, $\forall rf$ is also assured that the correct/expected instrumented code was executed to produce this log. By knowing the code, its control-flow, and all inputs, $\forall rf$ can locally emulate its execution and verify all steps in this computation, as well as detect all data-only and control-flow attacks.

B. Adversary Model

We assume an adversary that controls $Prv$’s entire software state, including code and data. It can modify any writable memory and read any memory that is not explicitly protected by hardware-enforced access controls, e.g., APEX rules. Program memory modifications can change instructions, while data memory modifications can trigger control-flow and data-only attacks arbitrarily. Adversarial modification attempts are allowed before, during, or after the execution.

C. Design Rationale

DIALED’s security is based on five features: F1-F5. We describe them at a high level in this section and discuss how to realize an instance of DIALED on MSP430 via automated code instrumentation in Section IV.

(F1) Integrity Proofs for Code, Instrumentation, and Output
As an instrumentation-based technique, DIALED is only secure if any modifications to the instrumented code itself (e.g., removing instrumented instructions) is detectable. Detection of code modifications is already offered by the underlying APEX PoX architecture (see Section II-C). APEX guarantees that every code modification is detected by \( Vrf \). It also guarantees that any modification of the attested executable’s output region \( OR \) (which, in our case, includes CF-Log and I-Log) can only be done by the attested executable itself, during its execution.

(F2) Integrity Proof for the Control Flow

Since DIALED relies on instrumented instructions, these instructions cannot be skipped, e.g., via control-flow violations. Therefore, Tiny-CFA ensures that the control flow is logged to Cf-Log and whatever is written to Cf-Log can not be modified; see [9] for details. Hence, all attempts to skip the logging of any data inputs are detectable by \( Vrf \) using Cf-Log. The integrity of Cf-Log itself is important to DIALED’s overall functionality, since \( Vrf \) needs both Cf-Log and I-Log in order to abstractly execute the program and verify the integrity of the execution.

(F3) Secure Logging of Data Inputs from Operation Arguments

To enable abstract execution by \( Vrf \), any arguments passed to the program at invocation must be securely logged to I-Log. DIALED automatically instruments the executable with Assembly instructions that copy all program arguments to I-Log.

(F4) Secure Logging of Runtime Data Inputs

In addition to arguments, data inputs can be obtained at runtime, e.g., sensed values read from GPIO, or packets arriving from the network. Such inputs are received through peripheral memory, at a particular set of physical addresses in data-memory. To detect and log these inputs DIALED instruments every \texttt{read} instruction to check whether the read address is outside the program’s stack. The range of the stack is determined by \([ls, hs]\), where \( ls \) is the value of the stack pointer saved at the moment when execution starts (before the allocation of local variables), and \( hs \) always reflects the current stack pointer, i.e., the top of the stack.

(F5) I-Log and Cf-Log Integrity

To ensure integrity of Cf-Log and I-Log, DIALED must guarantee that control flow and data-only attacks do not overwrite these logs. Thus, we realize I-Log and Cf-Log as a single stack data structure inside OR, from the highest value \((OR_{\text{max}})\) growing downwards. The pointer to the top of this stack is stored in a dedicated register \( R \). Each instruction that alters the control flow or involves data input is instrumented (with additional instructions) to push the relevant values (either control-flow destination or data input) onto the stack, i.e.:  
1) Write the value (destination of address or data input) to the location pointed by \( R \); and  
2) Decrement \( R \).
At instrumentation time, assembly code is inspected to ensure that no other instructions use \( R \). In all practical code examples we inspected, executables have at least one free register available. If no such register exists, the code can be recompiled to free up one register. Whenever a write operation occurs, it is checked for safety, by seeing if the address of the write is within the range \([R, OR_{\text{max}}]\), i.e., the current range for I-Log and Cf-Log. If an illegal write occurs, execution is aborted and \( Vrf \) treats it as an attack. Since these “write checks” are already needed, and implemented, by Tiny-CFA, they can be used “as is” by DIALED, at no additional instrumentation cost.

D. Security Analysis

Let \( Op \) denote an embedded operation for which control-flow and data-flow need to be attested. Feature \texttt{F1} assures to \( Vrf \) that \( Op \) indeed executed, and that neither its executable (including instructions added by DIALED’s instrumentation) nor the output (OR) produced by this execution has been tampered with. Feature \texttt{F2} assures that all changes to the control-flow of \( Op \) are written to \( OR \) at runtime. Similarly, \texttt{F3} & \texttt{F4} guarantee that any data inputs are also logged to \( OR \). Therefore, what we need to show is that, once written, control-flow and data input values in \( OR \) can not be modified during the rest of \( Op \) execution. This is exactly the guarantee offered by \texttt{F5}.

Therefore, DIALED features \texttt{F1-F5} suffice to guarantee the integrity of \( OR \) and \( Op \)’s executable (stored in \( ER \)), including I-Log and Cf-Log, even in the presence of potential control-flow and data-only attacks. Given the integrity of received I-Log and Cf-Log, \( Vrf \) can emulate execution of \( Op \) locally and reproduce any type of runtime attack that may have occurred during \( Op \)’s actual execution in \( Prv \).

IV. DIALED Implementation

As described in Section III-C, features \texttt{F1}, \texttt{F2} and \texttt{F5} are provided by APEX and Tiny-CFA. Hence, we focus on the implementation of \texttt{F3-F4} achieved via automated instrumentation of the executable. Our instrumentation component was coded in about 300 lines of Python. In the rest of this section we use \texttt{Op} to refer to the executable to be instrumented and later attested.

Figure 4 shows the instrumentation used to implement \texttt{F3} (in MSP430 Assembly) which commits \( Op \)’s arguments to I-Log. The instrumentation is added once: at the entry point of \( Op \) to log any input parameters. Lines 2-4 are already added to \( Op \) by Tiny-CFA to check whether \( R \) is initialized to \( OR_{\text{MAX}} \). This is required by property \texttt{F5} (see Section III-C). Lines 5-9 are added by DIALED to save the current stack pointer value to address \( OR_{\text{MAX}} \). This value determines the bottom of \( Op \)’s execution stack and is used to detect and log data inputs. Lines 10-25 copy \( Op \)’s arguments (input parameters) to I-Log. In MSP430, function arguments are passed using up to 8 general-purpose registers \( r8 \sim r15 \). Since the application defines how many arguments are passed, DIALED always logs all of such registers, to guarantee that all inputs are always captured. In this implementation, \( R = r4 \). Hence, each register is written to the memory address pointed by \( r4 \). At each such write, safety checks discussed in \texttt{F5} (Section III-C) are performed to assure the integrity of I-Log and Cf-Log in \( OR \). Additional checks are performed to guarantee that \( R = r4 \) never overflows the size of \( OR \). Such an event is treated as a security violation and reported to \( Vrf \).

Figure 5 depicts the instrumentation used to log runtime data inputs to I-Log—i.e., feature \texttt{F4}. Line 2 is a read instruction to copy contents from address pointed to by \( r15 \), to \( r14 \). In order to define whether this is indeed a data input, at line 4, the address in \( r15 \) is checked against the location of the bottom of \( Op \)’s stack, which is stored at the address of \( OR_{\text{MAX}} \) when \( Op \) is invoked (lines 6-9 in Figure 4). Also, at line 6 in Figure 5, the address in \( r15 \) is also checked against the current stack pointer (always stored at register \( r1 \)). If these checks fail, the value of the address pointed to by \( r15 \) lies outside of \( Op \)’s current execution stack: it is treated as input and committed to I-Log at line 9. Otherwise, the value is part of \( Op \)’s current state and is not logged. Lines 10-12 check if \( r4 \) reached the top of \( OR \), preventing overflows, as described in the previous paragraph.
Table I

| Technique | Support for CFA | Support for DFA | Hardware Cost – LUTs | Hardware Cost – Registers |
|-----------|-----------------|-----------------|---------------------|---------------------------|
| MSP430 (baseline) | – | – | 1904 | 691 |
| C-FLAT | ✓ | – | ARM-TrustZone | ARM-TrustZone |
| OAT | ✓ | – | ARM-TrustZone | ARM-TrustZone |
| Atrium | – | – | 10640 (+559%) | 15960 (+2308%) |
| LO-FAT | ✓ | – | 3192 (+168%) | 4256 (+616%) |
| LiteHAX | ✓ | – | 1596 (+84%) | 2128 (+308%) |
| Tiny-CFA | ✓ | – | 1904 (+16%) | 44 (+6%) |
| **DIALED** | ✓ | ✓ | 302 (+16%) | 44 (+6%) |

TABLE I

Functionality and Hardware Overhead Comparison of Existing Run-Time Attestation Architectures

same open-source applications used to evaluate Tiny-CFA: (1) Open-SyringePumpe⁵ – a medical syringe pump; (2) FireSensor¹; and (3) UltrasonicRanger⁶ – a sensor used in vehicles to measure distance from obstacles.

We consider all sources of runtime overhead imposed by code instrumentation in these techniques: code size increase, runtime (CPU cycles), and the size of the attestation log inside OR, including I-Log and CF-Log. Figures 6(a) and 6(b) compare results unmodified applications, with the same applications instrumented by Tiny-CFA (CFA guarantee only), and the same applications instrumented by DIALED (both CFA and DFA guarantees). As these results demonstrate, the overhead in both cases is dominated by the instrumentation required for CFA. On top of Tiny-CFA, DIALED code size and runtime increases range between 1% – 20%. This is due to additional instructions introduced by DIALED instrumentation, as described in Section IV. Figure 6(c) shows the total OR size required to store the execution information. Recall that DIALED requires storage of both 1-Log and CF-Log to enable detection of both control-flow and data-only attacks. Size requirement for these logs vary widely depending on the type of application (control-flow- or data-input-intensive). In general, we observe a small increase in OR size. This is due to the data input definition from Section III-C, which allows DIALED to only log relevant data inputs while retaining all necessary information for Vrf’s abstract execution of Prv’s embedded operation.

**Remark:** we do not compare runtime overhead of DIALED with DFA architectures LiteHAX and OAT, since these techniques rely on specific hardware support implemented in different CPU architectures (generally higher-end platforms), with different applications.

In summary, even though DIALED’s overhead is certainly not negligible, it is well within the capabilities of low-end MCUs and suitable for practical purposes. Specifically, instrumented binary sizes are within the MCUs memory budget, its runtime is reasonable, and log sizes are small enough to fit into data memory without encroaching on the stack. We believe this to be a reasonable price for the benefit of detecting any runtime compromise in low-end MCUs.

Note that, since DIALED is implemented alongside Tiny-CFA, it cannot be avoided by control flow attacks that jump in the middle of the instrumented code to skip checks and/or data input logging. Such an illegal jump is itself a control-flow change, which is committed to CF-Log by Tiny-CFA and thus detected by Vrf.

V. EVALUATION

We evaluate DIALED in terms of its hardware costs and software runtime overhead of attested embedded operations.

A. Hardware Overhead

Table I compares DIALED functionality and hardware costs to prior runtime attestation techniques (overviewed in Section VI). In terms of hardware, both C-FLAT [2] and OAT [21] are based on ARM TrustZone [4] which is inapplicable to low-end MCUs. Atrium [23], LO-FAT [11] and LiteHAX [10] rely on dedicated hardware support from hash engines and branch-monitoring modules. Thus, their hardware overhead is far more costly than the baseline MCU (MSP430) itself. Meanwhile, DIALED and Tiny-CFA rely exclusively on low-cost hardware support of the APEX’s PoX architecture [18]. Thus, they impose much lower hardware overhead, affordable even for such low-end MCUs. Out of all other architectures, only OAT, LiteHAX and DIALED provide both CFA and DFA. Among these, DIALED achieves ≈ 5× lower overhead in terms of combinational logic (Look-Up Tables – LUTs) and ≈ 50x lower state hardware overhead (Registers) than the cheapest prior technique achieving both CFA and DFA, i.e., LiteHAX.

B. Experimental Analysis on Real-world Applications

We evaluate DIALED runtime overhead in three real-world applications. For the sake of fair comparison, we consider the exact
Control-Flow and Data-Flow Integrity [1], [7] are techniques for prevention or detection of data and control-flow corruptions in real-time, locally at $Prv$, with after-the-fact detection by $Vrf$. All such techniques depend on complex software support (e.g., high-end operating systems) and/or heavyweight address-based and value-based integrity checks at runtime. Unfortunately, all these options are inapplicable to simple MCUs.

(Static) Remote Attestation (RA) [12], [8], [3], [13], [6], [17] is used by $Vrf$ to check if a remote $Prv$ has the proper software. By itself, static RA does not provide any runtime guarantees. However, it is used as a building block for most runtime attestation techniques, including CFA and DFA. DIALED itself is build atop APEX PoX functionality. In turn, APEX relies on VRASED [8] – a formally verified static RA architecture – to implement PoX.

Runtime Attestation includes techniques such as CFA and DFA. C-FLAT [2] is the earliest CFA architecture that uses ARM TrustZone Secure World [5] to implement CFA, by instrumenting the executable with context switches between TrustZone Normal and Secure worlds. At each control flow altering instruction, execution is trapped into Secure World and the control flow path is logged to protected memory. To remove TrustZone dependence, LO-FAT [11] and LiteHAX [10] implement CFA using stand-alone hardware modules: a branch monitor and a hash engine. Atrium [23] enhances aforementioned CFA techniques by securing them against physical adversaries that intercept instructions as they are fetched to the CPU. Though less expensive than C-FLAT, such hardware components are still not affordable for low-end MCUs, since their cost (in terms of price, size, and energy consumption) is higher than that of a low-end MCU itself. OAT [21] and LiteHAX [10] also provide DFA (in addition to CFA). However, similar to aforementioned techniques, they are too costly for low-end MCUs.

VII. CONCLUSIONS

We design and implement DIALED, the first Data-Flow Attestation (DFA) approach targeting lowest-end MCUs. DIALED is composed with Tiny-CFA, a Control-Flow Attestation (CFA) architecture, thus enabling detection of both control-flow and data-flow attacks at runtime. We discuss DIALED’s security and evaluate its performance on real embedded applications, showing that DIALED’s overhead is well within the capabilities of some of the most resource-constrained MCUs.

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