# The design of scalar AES Instruction Set Extensions for RISC-V

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**Abstract.** Secure, efficient execution of AES is an essential requirement for most computing platforms. Dedicated Instruction Set Extensions (ISEs) are often included for this purpose. RISC-V is a (relatively) new ISA that lacks such a standardised ISE. We survey the state-of-the-art industrial and academic ISEs for AES, implement and evaluate five different ISEs, one of which is novel, and make recommendations for standardisation. We consider the side-channel security implications of the ISE designs, demonstrating how an implementation of one candidate ISE can be hardened against DPA-style attacks. We also explore how the proposed standard Bit-manipulation extension to RISC-V can be harnessed for efficient implementation of AES-GCM. Our work supports the ongoing RISC-V cryptography extension standardisation process.

**Keywords:** ISE, AES, RISC-V

## 1 Introduction

**Implementing the Advanced Encryption Standard (AES).** Compared to more general workloads, cryptographic algorithms like AES present a significant implementation challenge. They involve computationally intensive and specialist functionality, are used in a wide range of contexts and form a central target in a complex attack surface. The demand for efficiency (however measured) is an example of this challenge in two ways. First, cryptography often represents an enabling technology vs. a feature and is often viewed as an overhead from a user's perspective. Addressing this is complicated by constraints associated with the context, e.g., a demand for high-volume, low-latency, high-throughput, low-footprint, and/or low-power implementations. Second, although efficiency is a goal in itself, it *also* acts as an enabler for security. This is because one *should not* compromise security to meet efficiency requirements. Hence a more efficient implementation leaves greater margin to deliver countermeasures against attack.

AES is an interesting case-study wrt. secure, efficient implementation. For example, per the request for candidates announcement,[1] the AES process was instrumental in popularising a model in which *both* "security" (e.g., resilience against cryptanalytic attack) *and* "algorithm and implementation characteristics" form important quality metrics for the *design*, in order to facilitate techniques for higher quality *implementations* of it. Additionally,

[1] https://www.govinfo.gov/content/pkg/FR-1997-09-12/pdf/97-24214.pdf

the design *and* implementations of AES are long-lived. The importance of AES has led to special emphasis on related research and development effort before, during, and, most significantly, after the AES process. The 20+ years since standardisation have forced an evolution of implementation techniques, to match changes in the technology and attack landscape. For example, [NBB+01, Section 3.6] covers implementation (e.g., side-channel) attacks: this field has become richer, and the associated threat more dangerous during said period.

**Support via Instruction Set Extensions (ISEs).** A large number of implementation styles often exist for a given cryptographic algorithm. Techniques can be algorithm-agnostic or algorithm-specific, and based on the use of hardware only, software only, or a hybrid approach using ISEs [GB11, BGM09, RI16]. For the ISE case, the aim is to identify through benchmarking, pieces of algorithm-specific functionality which are inefficiently represented in the base ISA. Said functions are then implemented in hardware, and exposed to the programmer via one or more new instructions.

ISEs are an effective option for *both* high-end, performance-oriented and low-end, constrained platforms. They are particularly effective for the latter where resource constraints are tightest. An ISE can be smaller and faster than a pure software implementation, and more efficient in terms of performance gain per additional logic gate than a hardware-only option.

Abstractly, an ISE design constitutes an *interface* to domain-specific functionality through the addition of instructions to a base ISA. As a fundamental and long-lived computer systems interface, the design and extension of an ISA demands careful consideration (cf. [Gue09, Section 4]). and the production of a concrete ISE design is not trivial. It must deliver a quantified improvement to the workload in question *and* consider numerous design goals including but not limited to:

- Limiting the number and complexity of changes and interactions with the parent ISA.
- Avoiding the addition of too many instructions, or requiring large additional hardware modules to implement. This will hurt commercial adoption of the ISA.
- Adhering to the design constraints and philosophies of the base ISA.
- Maximising the utility of the additional functionality, i.e., favour general-purpose over special-purpose functionality. Special-purpose functions can be justified in terms of how frequently the workload is required. For example, though an AES ISE might *only* be useful for AES, a webserver might execute AES millions of times per day.

The x86 architecture provides many examples of ISE design, having been extended numerous times by Intel and AMD. Various generations of non-cryptographic Multi-Media eXtensions (MMX), Streaming SIMD Extensions (SSE), and Advanced Vector Extensions (AVX) support numerical algorithms via vector (or SIMD) vs. scalar computation. Likewise, the cryptographic Advanced Encryption Standard New Instructions (AES-NI) [Gue09, DGvK19] ISE supports AES: it significantly improves latency and throughput (see, e.g., [FHLdO18]), and represents a useful casestudy in the design goals above: it adds just 6 additional (vs. 1500+ total) instructions, reduces overhead by sharing the pre-existing XMM register file, and facilitates compatibility via the `CPUID` [X8618a, Chapter 20] feature identification mechanism. It is also (sometimes un-expectedly) useful beyond AES: the Grøstl hash function [GKM+11] uses the S-box, and the YAES [BV14] authenticated encryption scheme uses a full round. It can even be used to accelerate the Chinese SM4 block cipher.[2]

**RISC-V.** RISC-V is a (relatively) new ISA, with academic origins [AP14, Wat16]. Unlike x86 or ARMv8-A, RISC-V is a free-to-use open standard, managed by RISC-V International.

[2] https://github.com/mjosaarinen/sm4ni

The base ISA is extremely simple, consisting of only 50 instructions, and adopts *strongly* RISC-oriented design principles. RISC-V is also highly modular, having been *designed to be extended*. The general-purpose base ISA can (optionally) be supplemented using sets of special-purpose, standard or non-standard extensions to support additional functionality (e.g., floating-point, via the standard F [RV:19a, Section 11] and D [RV:19a, Section 12] extension), or satisfy specific optimisation goals (e.g., code density, via the standard C [RV:19a, Section 16] extension). RISC-V International delegates the development of extensions to a dedicated task group. The Cryptographic Extensions Task Group[3] provides some specific context for this paper, through their remit to develop scalar and vector extensions to support cryptography.

RISC-V uses 32 registers denoted $\mathsf{GPR}[i]$, for $0 \leq i < 32$, and uses XLEN to denote the register bit-width of the base ISA. $\mathsf{GPR}[0]$ is fixed to 0, while $\mathsf{GPR}$s $1-31$ are general purpose. We focus on extending the RV32I [RV:19a, Section 2] and RV64I [RV:19a, Section 5], integer RISC-V base ISA and hence focus on systems where $\text{XLEN} = 32$ or $\text{XLEN} = 64$.

**Remit and organisation.** Set against on going effort to standardise cryptographic ISEs for RISC-V, this paper investigates support for AES. In specific terms, our contributions are as follows:

1. In Section 2 we capture some background, including a limited Systematisation of Knowledge (SoK) for AES ISEs.
2. In Section 3 we implement and evaluate five different ISEs for AES on two different RISC-V CPU cores. We explore existing ISE designs, and introduce what is, to the best of our knowledge, a novel ISE design in Section 3.5 that uses a quadrant-packed state representation.
3. In Section 4 we evaluate how the proposed standard Bit-manipulation extension [RV:19a, Section 21] to RISC-V can be used to efficiently implement AES-GCM.
4. In Section 5 we select one candidate ISE design from Section 3, and demonstrate how the associated implementation can be hardened against DPA-style attacks.

On the one hand, RISC-V represents an excellent target for such work: the ISA is extensible by design and its open nature makes exploration of extensions easier through the availability of (often open-source) implementations. Increased commercial deployment of such implementations suggests that work on RISC-V is timely and potentially of high impact. On the other hand, RISC-V also presents unique challenges vs. previous work. For example, RISC-V could in fact be viewed as *three* related base ISAs, RV32I [RV:19a, Section 2], RV64I [RV:19a, Section 5], and RV128I [RV:19a, Section 6], that each support a different word size: designing ISEs that are applicable (or scale) across these options is a complicating factor. We hope this work supports RISC-V in becoming the first widely implemented ISA to support AES acceleration across all implementation profiles, from embedded IoT devices to application and server class processors.

## 2 Background

FIPS-197 [FIP01] represents the definitive specification of AES. An overview of related design rationale is offered in [DR02]. We endeavour to follow the notation set out in [FIP01] in referencing specific parts of AES functionality.

[3] `https://lists.riscv.org/g/tech-crypto-ext`

## 2.1 AES implementation

### 2.1.1 Representation

A field element in $\mathbb{F}_{2^8}$ can be represented by an 8-bit byte where the $i$-th bit of $x$ for $0 \le i < 8$ represents the $i$-th polynomial coefficient.

Beyond this, the state and round key matrices can be represented in several ways. The most direct option would be termed array-based (or unpacked): the matrix is represented as a 16-element array of 8-bit bytes, each representing field elements. FIPS-197 [FIP01] defines a word to be st. $w = 32$. We use $R$ to refer to the register width of a target platform. For RISC-V, $R = \text{XLEN}$ where we consider $\text{XLEN} \in 32, 64$. Where $R \ge 32$, an entire row or column of the AES state matrix can be packed into each register: we term these "row-packed" and "column-packed" representations respectively. Where $R \ge 128$, it is plausible to pack an entire AES state matrix into a single register: we term this a "fully-packed" representation.

### 2.1.2 Hardware-only implementations

In a hardware-only implementation, execution of AES is performed by a dedicated hardware module (e.g., a memory-mapped co-processor), while the software which uses AES is executed on a general-purpose CPU core. A large design space exists for hardware implementations of AES. Gaj and Chodowiec [GC00, Section 3.3] give an overview, detailing iterative, combinatorial (unrolled), and pipelined architectures. Similarly, [PMDW04, GB05, GC09] survey concrete implementations on a variety of fabrics including FPGAs and ASICs.

Although hardware-only designs are not our focus, the associated techniques inform ISE-related design choices. First, they inform the ISE interface. For example, some ISEs can be characterised as offering an interface to hardware constituting one round (i.e., aligned with an iterative hardware implementation). Second, they inform the ISE implementation. For example, a significant body of work focuses on efficient hardware implementation of the S-box: [Can05, BP12, RMTA18].

### 2.1.3 Software-only implementations

In a software-only implementation, execution of AES and the associated application program is performed by a general-purpose processor core, using only instructions in the base ISA. Since we only consider use of the RISC-V scalar base ISA, we exclude work on the use of vector-like extensions [Ham09].

Software-only techniques are important because many ISEs are evaluated against baseline ISA implementations. Work such as that of Bernstein and Schwabe [BS08], Osvik et al. [OBSC10], and Schwabe and Stoffelen [SS16] present and compare multiple techniques across a range of platforms, but, for completeness, we present a (limited) survey in what follows.

**Compute-oriented.** A compute-oriented implementation of AES favours online computation, thus reducing memory footprint at the cost of increased latency. Following [DR02, Section 4.1], for example, the idea is to simply 1) adopt an array-packed representation of state and round key matrices, then 2) construct a round implementation by following the algorithmic description of each round function in a direct manner. Addition in $\mathbb{F}_{2^8}$ can be implemented with a base ISA XOR instruction. Base ISA support is rarely present for multiplication and inversion in $\mathbb{F}_{2^8}$ however. Hence it is common to pre-compute the S-box and/or `xtime` functions. This requires pre-computation and storage of a 256 B look-up table per function, but significantly reduces execution latency.

On platforms where $R = 32$, Bertoni et al. [BBF+02] improve execution latency by exploiting the wider data-path. They adopt a row-packed representation of state and round key matrices, implementing `ShiftRows` using native rotation instructions to act on the packed rows. `MixColumns` is implemented using the SIMD Within A Register (SWAR) paradigm: applying `xtime` across a packed row in parallel.

**Table-oriented.** A table-oriented implementation of AES favours offline pre-computation, reducing latency but increasing the memory footprint. The main example of this technique is the so-called T-tables [DR02, Section 4.2] method. This involves adopting a column-packed representation of state and round key matrices and pre-computing `MixColumn` $\circ$ `SubBytes` using the tables

$$T_0[x] = \begin{bmatrix} 02_{(16)} \otimes \text{S-BOX}(x) \\ 01_{(16)} \otimes \text{S-BOX}(x) \\ 01_{(16)} \otimes \text{S-BOX}(x) \\ 03_{(16)} \otimes \text{S-BOX}(x) \end{bmatrix} \qquad T_1[x] = \begin{bmatrix} 03_{(16)} \otimes \text{S-BOX}(x) \\ 02_{(16)} \otimes \text{S-BOX}(x) \\ 01_{(16)} \otimes \text{S-BOX}(x) \\ 01_{(16)} \otimes \text{S-BOX}(x) \end{bmatrix}$$

$$T_2[x] = \begin{bmatrix} 01_{(16)} \otimes \text{S-BOX}(x) \\ 03_{(16)} \otimes \text{S-BOX}(x) \\ 02_{(16)} \otimes \text{S-BOX}(x) \\ 01_{(16)} \otimes \text{S-BOX}(x) \end{bmatrix} \qquad T_3[x] = \begin{bmatrix} 01_{(16)} \otimes \text{S-BOX}(x) \\ 01_{(16)} \otimes \text{S-BOX}(x) \\ 03_{(16)} \otimes \text{S-BOX}(x) \\ 02_{(16)} \otimes \text{S-BOX}(x) \end{bmatrix}$$

for $x \in \mathbb{F}_{2^8}$, 3) computing each $j$-th column of $s^{(r+1)}$ as

$$T_0[s^{(r)}_{i,j+i \pmod{Nb}}] \oplus T_1[s^{(r)}_{i,j+i \pmod{Nb}}] \oplus T_2[s^{(r)}_{i,j+i \pmod{Nb}}] \oplus T_3[s^{(r)}_{i,j+i \pmod{Nb}}]$$

where extraction of elements caters for `ShiftRows`, then XOR'ing the $j$-th column of $rk^{(r)}$ to cater for `AddRoundKey`.

As such, each round becomes a sequence of look-ups into $T_i$, plus XORs to combine their result. Doing so demands pre-computation and storage of a $256 \cdot 4\,\text{B} = 1\,\text{kB}$ look-up table per $T_i$. The overhead related to extraction of each element from packed columns representing $s^{(r)}$ (to form look-table offsets) can be significant: Fiskiran and Lee [FL01] analyse the impact of different addressing modes on this issue, with Stoffelen [Sto19, Section 3.1] concluding that RISC-V is ill-equipped to reduce said overhead, due to the provision of a sparse set of addressing modes.

**Bit-sliced.** The term bit-slicing is an implementation technique due to Biham [Bih97], which constitutes

1. a non-standard *representation* of data where each $R$-bit word $x$ is transformed into $\hat{x}$, i.e., $R$ slices, say $\hat{x}[i]$ for $0 \le i < R$, where $\hat{x}[i]_j = x_i$ for some $j$, and
2. a non-standard *implementation* of operation: each operation $f$ used as $r = f(x)$ must be transformed into a "software circuit" $\hat{f}$, i.e., a sequence of Boolean instructions acting on the slices st. $\hat{r} = \hat{f}(\hat{x})$.

Bit-slicing introduces some overhead related to conversion of $x$ into $\hat{x}$ and $\hat{r}$ into $r$, plus the (relative) inefficiency of $\hat{f}$ vs. $f$ wrt. latency and footprint. However, if each slice is itself an $R$-bit word, then it is possible to compute $R$ instances of $\hat{f}$ in *parallel* on suitably packed $\hat{x}$. A common analogy is that of transforming the $R$-bit, 1-way scalar processor into a 1-bit, $R$-way SIMD processor, thus giving (or recouping) up to a $R$-fold improvement in latency.

As evidenced by [MN07, Kö08] and [KS09], the application of bit-slicing to AES can be very effective; Stoffelen [Sto19, Section 3.1] specifically investigates this fact within the context of RISC-V.

## 2.2 Existing AES ISEs

Here, we survey AES-related ISE designs split into 1) industry-specified ISEs, which are *standard* extensions, and 2) academia-specified ISEs, which are *non-standard* extensions, wrt. a given base ISA. Each ISE is classified as either workload-specific, if it is only useful for AES, or workload-agnostic, if it is useful for AES and other workloads. Note that we exclude work where an ISE for another workload can be applied *to* AES but was not designed *for* AES (see, e.g., Tillich and Großschädl [TG04] who apply an ISE intended for ECC to AES).

### 2.2.1 Standard, industry-specified ISEs.

**Intel.** Introduced support for AES in x86 per [X8618a, Section 12.13]. Instructions use a destructive 2-address (1 source, 1 source/destination) or non-destructive 3-address (2 source, 1 destination) format depending on the variant (e.g., XMM- vs. AVX-based), and operate on data housed in the pre-existing vector register file, implying $R = 128$. AES is implemented by 1) adopting a fully-packed representation of state and round key matrices, then 2) using `AESENC` [X8618b, Page 3-54] to construct a round implementation as

$$\texttt{AESENC} \mapsto \texttt{AddRoundKey} \circ \texttt{MixColumns} \circ \texttt{SubBytes} \circ \texttt{ShiftRows}$$

**IBM.** Introduced support for AES in POWER per [POW18, Section 6.11.1]. Instructions use a non-destructive 3-address (2 source, 1 destination) format, and operate on data housed in the pre-existing vector register file, implying $R = 128$. AES is implemented by 1) adopting a fully-packed representation of state and round key matrices, then 2) using `vcipher` [POW18, Page 304] to construct a round implementation as

$$\texttt{vcipher} \mapsto \texttt{AddRoundKey} \circ \texttt{MixColumns} \circ \texttt{ShiftRows} \circ \texttt{SubBytes}$$

**ARM.** Introduced support for AES in ARMv8-A per [ARM20, Section A2.3]. Instructions use a destructive 2-address (1 source, 1 source/destination) format, and operate on data housed in the pre-existing vector register file, implying $R = 128$. AES is implemented by 1) adopting a fully-packed representation of state and round key matrices, then 2) using `AESE` [ARM20, Section C7.2.8 ] and `AESMC` [ARM20, Section C7.2.10] to construct a round implementation as

$$\texttt{AESMC} \circ \texttt{AESE} \mapsto \texttt{MixColumns} \circ (\texttt{SubBytes} \circ \texttt{ShiftRows} \circ \texttt{AddRoundKey}),$$

**Oracle.** Introduced support for AES in SPARC per [SPA16, Sections 7.3+7.4]. Instructions use a non-destructive 4-address (3 source, 1 destination) format, and operate on data housed in the pre-existing general-purpose register file, implying $R = 64$. AES is implemented by 1) using a column-packed representation of state and round key matrices, then 2) using `AES_EROUND01` [SPA16, Page 109] and `AES_EROUND23` [SPA16, Page 109] to construct a round implementation as

$$(\texttt{AES\_EROUND01}; \texttt{AES\_EROUND23}) \mapsto \texttt{AddRoundKey} \circ \texttt{MixColumns} \circ \texttt{ShiftRows} \circ \texttt{SubBytes}$$

in two steps: the first step processes columns 0 and 1 via `AES_EROUND01` whereas the second step processes columns 2 and 3 via `AES_EROUND23`.

### 2.2.2 Non-standard, academia-specified ISEs.

Burke et al. [BMA00] propose a workload-agnostic ISE based on workload characterisation. Per [BMA00], pertinent examples for AES include a) `ROL` and `ROR`, which perform left-

and right-rotate, and b) `SBOX`, which extracts elements to form look-up table offsets. In one configuration, the resulting memory accesses are supported by a set of special-purpose “S-box caches”.

Fiskiran and Lee [FL05] propose a workload-agnostic ISE that employs a so-called Parallel Table Lookup Module (PTLU). For AES, this accelerates implementations based on T-tables by affording an addressing mode that a) integrates extraction of elements to form look-up table offsets, and b) performs the associated table look-ups in parallel, supported by a dedicated scratch-pad memory.

Biham et al. [BAK98, Page 232] propose (in theory) and Grabher et al. [GGP08] explore (in practice) a workload-agnostic ISE that supports bit-sliced implementations. The ISE allows computation using *configurable* 4-input, 2-output Boolean functions, vs. *fixed* 2-input, 1-output alternatives such as NOT, AND, OR, and XOR. Sequences of native Boolean instructions, which dominate bit-sliced implementations, can thereby be “compressed” into use of the ISE. Doing so improves both latency and footprint. [GGP08, Section 4] details the application to AES.

Nadehara et al. [NIK04] propose a workload-specific ISE that could be described as “hardware-assisted T-tables”: observing that $\forall x, i \neq j$, $T_i[x]$ is a rotation of $T_j[x]$, they support on-the-fly computation (vs. via look-up) of T-table entries. The ISE constitutes a single instruction $\texttt{AESENC} \mapsto T_i$, supported by a dedicated hardware module (see [NIK04, Figure 6]). Instances of `AESENC` 1) extract an input element from a packed input column 2) use the input to compute an output element equivalent to a look-up from the T-table, and 3) store the output element into a packed output column. This approach was reapplied by Saarinen [Saa20] within the context of RISC-V.

Tillich et al. [TGS05] propose a workload-specific ISE that could be described as “hardware-assisted S-box”. The ISE constitutes a single instruction $\texttt{sbox} \mapsto \texttt{SubBytes}$, supported by a dedicated hardware module (see [TGS05, Figure 1]). Instances of `sbox` 1) extract an input element from a packed input row or column, 2) use the input to compute an output element equivalent to a look-up from the S-box, and 3) insert the output element into a packed output row or column. Using insert vs. overwrite semantics allows `ShiftRows` to be computed *for free*.

Bertoni et al. [BBFR06] propose a workload-specific ISE that could be described as “hardware-assisted round functions”. Per [BBFR06, Section 4], the ISE includes 1) zero-overhead rotation (similar to ARM), and 2) byte- and word-oriented variants of $\texttt{SMix} \mapsto \texttt{MixColumn} \circ \texttt{SubBytes}$.

Tillich and Großschädl [TG06] propose a workload-specific ISE that could be described as “hardware-assisted round functions”. Per [TG06, Section 4], the ISE includes byte- and word-oriented variants of $\texttt{sbox[4][s|r]} \mapsto \texttt{SubBytes}$ and $\texttt{mixcol[4][s]} \mapsto \texttt{MixColumn}$; per [TG06, Section 4.3], the most efficient variant allows a zero-overhead implementation of `ShiftRows` to be realised.

## 2.3 Security

While the security of AES against a cryptanalytic attack is defined by the design, and so is out of scope, *implementation* attacks are of central importance. An implementation attack focuses on the concrete instance of a construct rather than the abstract specification. Countermeasures against such attacks must therefore be considered alongside implementations they relate to. As AES is an important target, a significant body of literature exists around implementation attacks on it, including both active (e.g., fault injection) or passive (i.e., side-channel monitoring) attack techniques. The latter can be sub-divided into those dependent on analogue (power-based [MOP07]) or discrete (time-based [KQ99]) leakage.

Use of ISEs *can* provide some inherent protection against certain attacks. For example, ISEs typically yield constant time execution, preventing some classes of timing or micro-architectural attack techniques. (See [Sze19, Section 4] and [GYCH18, Section 4])

Unfortunately, use of ISEs also presents some unique challenges. For example, Saab et al. [SRH16] discuss power-based attacks on AES-NI; concluding that naive use of AES-NI yields exploitable information leakage. Mitigation of such leakage demands the ISE address instances where the leakage stems from "inside" the ISE, and work with appropriate countermeasures (e.g., hiding [MOP07, Chapter 7] or masking [MOP07, Chapter 10]). Tillich et al. [THM07] consider this problem to an extent, including an ISE-based option in their investigation of hardened AES implementations. However, the challenge of developing suitable ISEs is under-studied in general. We investigate this further in Section 5.

## 3 Exploring AES ISEs for RISC-V

Section 2.2 outlined a range of ISE designs, demonstrating a large design space of options that we *could* consider. To narrow the design space into those we *do* consider, we use the requirements outlined below:

**Requirement 1.** *The ISE must support 1) AES encryption* and *decryption, and 2)* all *parameter sets, i.e., AES-128, AES-192, and AES-256. Support for auxiliary operations, e.g., key schedule, is an advantage but not a requirement.*

**Requirement 2.** *The ISE must align with the wider RISC-V design principles. This means it should favour simple building-block operations, and use instruction encodings with at most* 2 *source registers and* 1 *destination register. This avoids the cost of a general-purpose register file with more than* 2 *read ports or* 1 *write port.*

**Requirement 3.** *The ISE must use the RISC-V general-purpose scalar register file to store operands and results, rather than any vector register file. This requirement excludes the majority of standard ISEs outlined in Section 2.2.*

**Requirement 4.** *The ISE must not introduce special-purpose architectural state, nor rely on special-purpose micro-architectural state (e.g., caches or scratch-pad memory).*

**Requirement 5.** *The ISE must enable data-oblivious execution of AES, preventing timing attacks based on execution latency (e.g., stemming from accesses to a pre-computed S-box).*

**Requirement 6.** *The ISE must be efficient, in terms of improvement in execution latency per area required: this balances the value in* both *metrics vs. an exclusive preference for one or the other. Efficiency wrt. auxiliary metrics, e.g., memory footprint or instruction encoding points, is an advantage but not a requirement.*

Overall, the requirements combine to intentionally target the ISE at low(er)-end, resource-constrained (e.g., embedded) platforms. We view such a focus as reasonable, because existing work on adding cryptographic support to the standard Vector extension [RV:19a, Section 21] already caters for high(er)-end alternatives.

We arrive at five ISE variants using the requirements, the description of which is split into an intuitive description in one of the following Sections and a technical description (e.g., a list of instructions and their semantics) in an associated Appendix.

### 3.1 Variant 1 ($\mathcal{V}_1$): `SubBytes` + `MixColumn` + explicit `ShiftRows`

By reproducing [TG06, Section 4.2], $\mathcal{V}_1$ assumes XLEN = 32 and adopts a column-packed representation of state and round key matrices.

As detailed in Figure 3 and Figure 4, $\mathcal{V}_1$ adds 4 instructions (2 for encryption, 2 for decryption). For example, `saes.v1.encs` applies `SubBytes` to elements in a packed column, and `saes.v1.encm` applies `MixColumn` to a packed column; the instruction format for `saes.v1.encs` and `saes.v1.encm` includes 1 source and 1 destination register address.

Since `saes.v1.encs` requires 4 applications of the S-box, a trade-off between latency and area is possible st. $n$ physical S-box instances are (re)used in $4/n$ cycles (e.g., 1 instance in 4 cycles, or 4 instances in 1 cycle).

Figure 5 demonstrates that use of $\mathcal{V}_1$ to implement AES encryption requires 47 instructions per round: 4 `lw` instructions to load the round key, 4 `xor` instructions to apply `AddRoundKey`, 4 `saes.v1.encs` instructions to apply `SubBytes`, 31 instructions to apply `ShiftRows`, and 4 `saes.v1.encm` instructions to apply `MixColumns`.

## 3.2 Variant 2 ($\mathcal{V}_2$): `SubBytes` + `MixColumn` + implicit `ShiftRows`

By reproducing [TG06, Section 4.3], $\mathcal{V}_2$ assumes XLEN = 32 and adopts a column-packed representation of state and round key matrices.

As detailed in Figure 7 and Figure 8, $\mathcal{V}_2$ adds 4 instructions (2 for encryption, 2 for decryption). For example, `saes.v2.encs` applies `SubBytes` to elements in a packed column, and `saes.v2.encm` applies `MixColumn` to a packed column; the instruction format for `saes.v2.encs` and `saes.v2.encm` includes 2 source and 1 destination register address. $\mathcal{V}_2$ improves $\mathcal{V}_1$ by applying `ShiftRows` *implicitly*: this is possible by careful indexing of elements in source and destination columns during application of `SubBytes` and `MixColumns`, and also permits `saes.v2.encs` to be used within the key schedule. The same trade-off is possible as in $\mathcal{V}_1$, whereby $n$ physical S-box instances are (re)used in $4/n$ cycles (e.g., 1 instance in 4 cycles, or 4 instances in 1 cycle).

Figure 9 demonstrates that use of $\mathcal{V}_2$ to implement AES encryption requires 16 instructions per round: 4 `lw` instructions to load the round key, 4 `xor` instructions to apply `AddRoundKey`, 4 `saes.v1.encs` instructions to apply `SubBytes`, and 4 `saes.v1.encm` instructions to apply `MixColumns`. In the $Nr$-th round, which omits `MixColumns`, `ShiftRows` must be applied *explicitly* using an additional 12 instructions.

## 3.3 Variant 3 ($\mathcal{V}_3$): hardware-assisted T-tables

$\mathcal{V}_3$ is based on [NIK04, BBFR06, Saa20]; it assumes XLEN = 32 and adopts a column-packed representation of state and round key matrices.

As detailed in Figure 11 and Figure 12, $\mathcal{V}_3$ adds 4 instructions (2 for encryption, 2 for decryption). The basic idea is to support an implementation strategy aligned with use of T-tables [DR02, Section 4.2], but compute entries in hardware vs. storing the look-up entries in memory. For example, `saes.v3.encsm` extracts an element from a packed column, applies `SubBytes` to the element, expands the element into a packed column, applies `MixColumn`, then applies `AddRoundKey`. The inclusion of `AddRoundKey` follows [Saa20], which improves on [NIK04, BBFR06]; as a result of this, the instruction format for `saes.v3.encsm` includes 2 source and 1 destination register address. The requirement for 1 application of the S-box allows for a more efficient functional unit than $\mathcal{V}_1$ or $\mathcal{V}_2$, for example, either wrt. latency or area.

Figure 13 demonstrates that use of $\mathcal{V}_3$ to implement AES encryption requires 20 instructions per round: 4 `lw` instructions to load the round key, and 16 `saes.v3.encsm` instructions to apply `SubBytes`, `ShiftRows`, `MixColumns`, and `AddRoundKey`. In the $Nr$-th round, which omits `MixColumns`, `saes.v3.encsm` is replaced by `saes.v3.encs`.

## 3.4 Variant 4 ($\mathcal{V}_4$): 64-bit data-path

$\mathcal{V}_4$ is similar to the SPARC [SPA16, Page 109] ISE in requiring XLEN = 64 and adopting a *double* column-packed representation of state and round key matrices, i.e., *two* columns (or 8 elements) are packed into a 64-bit word. While still adhering to a format that includes 2 source and 1 destination register address, a single instruction can therefore 1) accept all of the current state as input, and 2) produce half of the next state as output.

$$s^{(r)} = \begin{bmatrix} s^{(r)}_{0,0} & s^{(r)}_{0,1} & s^{(r)}_{0,2} & s^{(r)}_{0,3} \\ s^{(r)}_{1,0} & s^{(r)}_{1,1} & s^{(r)}_{1,2} & s^{(r)}_{1,3} \\ s^{(r)}_{2,0} & s^{(r)}_{2,1} & s^{(r)}_{2,2} & s^{(r)}_{2,3} \\ s^{(r)}_{3,0} & s^{(r)}_{3,1} & s^{(r)}_{3,2} & s^{(r)}_{3,3} \end{bmatrix} \mapsto \begin{bmatrix} \begin{bmatrix} s^{(r)}_{0,0} \\ s^{(r)}_{1,0} \\ s^{(r)}_{0,1} \\ s^{(r)}_{1,1} \end{bmatrix} \begin{bmatrix} s^{(r)}_{0,2} \\ s^{(r)}_{1,2} \\ s^{(r)}_{0,3} \\ s^{(r)}_{1,3} \end{bmatrix} \begin{bmatrix} s^{(r)}_{2,0} \\ s^{(r)}_{3,0} \\ s^{(r)}_{2,1} \\ s^{(r)}_{3,1} \end{bmatrix} \begin{bmatrix} s^{(r)}_{2,2} \\ s^{(r)}_{3,2} \\ s^{(r)}_{2,3} \\ s^{(r)}_{3,3} \end{bmatrix} \end{bmatrix}$$

Figure 1: An illustration of quadrant-packed representation, as applied to a state matrix.

SPARC [SPA16, Page 109] adds 9 instructions (4 for encryption, 4 for decryption, and 1 auxiliary). For example, `AES_EROUND01` and `AES_EROUND23` produce columns 0 and 1 and columns 2 and 3 respectively. As detailed in Figure 15 and Figure 16, $\mathcal{V}_4$ refines this slightly by adding 7 instructions (2 for encryption, 2 for decryption, and 3 auxiliary). For example, `saes.v4.encs` applies `SubBytes`, `ShiftRow`, and `MixColumn` to elements in a packed column, but differs from `AES_EROUND01` and `AES_EROUND23`, because 1) it constitutes 1 (vs. 2) instruction, which is possible by observing that swapping the inputs allows computation of either columns 0 and 1 or columns 2 and 3, and 2) it uses 2 (vs. 3) source register addresses, as a result of opting not to include `AddRoundKey`.

Figure 17 demonstrates that use of $\mathcal{V}_4$ to implement AES encryption requires 6 instructions per round: 2 `ld` instructions to load the round key, 2 `xor` instructions to apply `AddRoundKey`, 2 `saes.v4.encsm` instructions to apply `SubBytes`, `ShiftRows`, and `MixColumns`. In the $Nr$-th round, which omits `MixColumns`, `saes.v4.encsm` is replaced by `saes.v4.encs`.

## 3.5 Variant 5 ($\mathcal{V}_5$): quadrant-packed

$\mathcal{V}_5$ assumes XLEN = 32 and adopts a novel, *quadrant*-packed representation of state and round key matrices: per Figure 1 for example, doing so packs each 4-element quadrant of the state into a 32-bit word. Note that *either* two rows *or* two columns of the state can be accessed by accessing two quadrants: the intuition, based on this fact, is that such a representation can 1) afford advantages of *both* row- and column-packed alternatives, *and* 2) allow an instruction format that includes 2 source and 1 destination register address. However, it also implies a need to convert any input into (resp. output from) *quadrant*-packed representation; although such conversion is amortised by $Nr$ rounds of computation, it represents an overhead vs. other variants.

As detailed in Figure 19 and Figure 20, $\mathcal{V}_5$ adds 7 instructions (3 for encryption, 3 for decryption, and 1 auxiliary). For example, `saes.v5.esrsub.lo` applies `SubBytes` and `ShiftRow` to the lower row spanning two packed quadrants, `saes.v5.esrsub.hi` applies `SubBytes` and `ShiftRow` to the upper row spanning two packed quadrants, and `saes.v5.emix` applies `MixColumn` to a column spanning two packed quadrants.

Figure 21 demonstrates that use of $\mathcal{V}_5$ to implement AES encryption requires 16 instructions per round: 4 `lw` instructions to load the round key, 4 `xor` instructions to apply `AddRoundKey`, 4 `saes.v5.esrsub.[lo|hi]` instructions to apply `SubBytes` and `ShiftRows`, and 4 `saes.v5.emix` instructions to apply `MixColumns`. Note that conversion into (resp. from) quadrant-packed representation requires a further 12 instructions; this can be reduced to 4 `pack[h]` instructions using the standard Bit-manipulation [RV:19a, Section 17] extension.

## 3.6 Implementation

The evaluation of each ISE considers two different RISC-V compliant base micro-architectures, which constitute two different host cores:

- The SCARV[4] core supports the RV32IMC instruction set, i.e., the 32-bit [RV:19a, Section 2] base integer ISA plus standard Multiplication [RV:19a, Section 7] and Compressed [RV:19a, Section 16] extensions. Per the block diagram shown in Figure 23, the core executes instructions using a 5-stage, in-order pipeline. No branch prediction is supported. There are two memory interfaces for instruction fetch and data memory accesses. No instruction or data caches are supported. The core implements various performance counters, and elements of the RISC-V Privileged Resource Architecture (PRA) [RV:19b, Chapter 3] related to exception and interrupt handling.
- The Rocket [AAB+16] core executes instructions using a 5-stage, in-order pipeline which is highly configurable. We take advantage of this, considering two variants whose exact configuration is outlined in Figure 25 and Figure 26: the variants represent single 32-bit and 64-bit cores respectively, and so support the RV32IMC (resp. RV64IMC) instruction set, i.e., the 32-bit [RV:19a, Section 2] (resp. 64-bit [RV:19a, Section 5]) base integer ISA plus standard Multiplication [RV:19a, Section 7] and Compressed [RV:19a, Section 16] extensions. Each variant is configured to support an instruction cache, a data cache, and a branch prediction mechanism, but no floating-point support.

To support each ISE, two modifications were made to each host core: the instruction decoder was modified to support operand selection and an AES Functional Unit (AES-FU) was added to support execution of ISE instructions. The SCARV core integrates the AES-FU directly into the pipeline, while the Rocket core accesses the AES-FU via the Rocket Custom Coprocessor (RoCC) [AAB+16, Section 4] interface. Due to Requirement 2, specifically that each instruction uses at most 2 source and 1 destination register, neither micro-architecture required further structural alteration. A synthesis-time parameter was used to switch between different ISEs.

## 3.7 Evaluation

**Hardware** Each ISE variant was integrated into the 3 host cores described in Section 3.6. The variants which assume XLEN = 32 ($\mathcal{V}_1$, $\mathcal{V}_2$, $\mathcal{V}_3$, and $\mathcal{V}_5$) were evaluated on *both* the 32-bit SCARV core *and* the 32-bit Rocket core; the variant which assumes XLEN = 64 ($\mathcal{V}_4$) was evaluated on *only* the 64-bit Rocket core. For $\mathcal{V}_1$, $\mathcal{V}_2$ and $\mathcal{V}_5$ a trade-off between latency and area exists. Each such case is considered through two optimisation goals: the (A)rea goal instantiates 1 S-box and has a $n$-cycle execution latency, whereas the (L)atency goal instantiates 4 S-boxes and has a 1-cycle execution latency.

Table 1 records various metrics associated with the hardware implementations, arranged in two parts: the left-hand part relates to each ISE in isolation, whereas the right-hand part relates to each ISE integrated with a given core. Throughout, both area (measured in NAND2 equivalent gates) and Circuit Depth are as reported by Yosys [Wol]. We found that none of the ISEs affected the critical path of either the SCARV or Rocket core. Considering each ISE as implemented on the Rocket core, we note the overhead wrt. area is marginal: this stems from the fact that the baseline area of Rocket includes the data and instruction caches.

**Software** We evaluated each ISE variant by implementing the AES-128 Enc, Dec *plus* Enc-KeyExp and Dec-KeyExp. We used a *non*-ISE T-table based implementation as a baseline. The variants which assume XLEN = 32 ($\mathcal{V}_1$, $\mathcal{V}_2$, $\mathcal{V}_3$, and $\mathcal{V}_5$) used a rolled strategy wrt. loops: $\mathcal{V}_1$, $\mathcal{V}_2$, and $\mathcal{V}_5$ used 1 round per iteration, whereas $\mathcal{V}_3$ used 2 rounds

[4] https://github.com/scarv/scarv

per iteration to avoid needless register move operations. The variant which assumes XLEN = 64 ($\mathcal{V}_4$) used an unrolled strategy. In all cases the state is naturally aligned,[5] meaning any input (resp. output) can be loaded (resp. stored) using 4 `lw` instructions on a 32-bit core or 2 `ld` instructions on a 64-bit core.

Table 2 records the memory footprint (i.e., code footprint and static data footprint) of each software implementation. Where an entry for Dec-KeyExp is zero, this implies that Enc-KeyExp = Dec-KeyExp so there is no overhead. Where an entry for Dec-KeyExp is non-zero, this implies that Enc-KeyExp $\neq$ Dec-KeyExp, and the equivalent inverse cipher construction [FIP01, Section 5.3.5] is used. This allows Dec-KeyExp to call Enc-KeyExp, then perform some additional post processing, with the quoted footprint therefore reflecting the latter only. Table 3 and Table 4 record instruction (i.e., iret) and cycle counts of each implementation, as executed on the SCARV and Rocket cores respectively.

**Discussion** Table 1 demonstrates that all ISE variants imply a modest area overhead relative to their host core. The RV32 Rocket area results are not listed, as the ISE overhead compared to the area of a synthesised Rocket Tile with caches was less than 1% in all cases. Table 2 shows all ISE variants having similarly small memory footprints in terms of both instruction code and data. Beyond this, and per Section 3, the primary metric of interest is efficiency in terms of improvement in execution latency per area: this metric draws on data from Table 1 plus either Table 3 or Table 4 for the SCARV or Rocket core respectively, and, for each variant, is computed by dividing the improvement in execution latency (relative to the T-table baseline) by the normalised area (i.e., the ISE area column of Table 1). We deliberately omit the area of the host core from this calculation, as this fixed overhead dominates the final value and detracts from the comparison between ISEs themselves.

Table 5 captures the results for the Rocket core, although the same conclusion can be drawn for the SCARV core. Qualitatively, we place more of a weight on Enc and Dec vs. Enc-KeyExp and Dec-KeyExp, because typically many Enc or Dec operations are performed per KeyExp. For a 32-bit core, our conclusion is that $\mathcal{V}_3$ is the best option. Despite not being the fastest (by a small margin), it is the most efficient, and simplest to implement. The area optimised $\mathcal{V}_2$ implementation sometimes comes close in efficiency, but requires a more complex multi-cycle implementation in this case. For a 64-bit core, $\mathcal{V}_4$ is the best option, which is somewhat obvious because it specifically makes use of the wider data-path. With reference to Table 4, note that the number of cycles per instruction executed is relatively low. This fact stems from use of the ROCC interface, in that forwarding of the result from an ISE instruction (that uses the ROCC) incurs an overhead vs. an ISE instruction; fine-grained integration of the AES-FU could therefore incrementally improve the results.

We believe it is sensible to standardise different ISEs for the RV32 and RV64 base ISAs. This allows each ISE design to better suit the constraints of each base ISA. In the RV32 case, this acknowledges that such cores will most often appear in resource-constrained, embedded or IoT class devices. Hence, the most efficient ISE design is appropriate. For necessarily larger RV64-based designs, it makes sense to take advantage of the wider data-path, and acknowledge that these are more likely to be application class cores. Hence, they will place a higher value on performance than area-efficiency.

## 4 Using ISEs to implement AES-GCM

[5] RISC-V does not mandate support for misaligned loads and stores, so aligning the state this way ensures the best performance across all cores.

Table 1: Hardware implementation metrics (e.g., area and Circuit Depth) for each ISE variant.

| ISA | Variant | (Goal) | ISE area | ISE Circuit Depth | SCARV + ISE area | |
|---|---|---|---|---|---|---|
| RV32IMC | | | | | 37375 | (1.00×) |
| RV32IMC | $\mathcal{V}_1$ | (L) | 3472 | **19** | 41723 | (1.12×) |
| RV32IMC | $\mathcal{V}_1$ | (A) | 2174 | 22 | 40161 | (1.07×) |
| RV32IMC | $\mathcal{V}_2$ | (L) | 3547 | **19** | 41199 | (1.10×) |
| RV32IMC | $\mathcal{V}_2$ | (A) | 1381 | 21 | 38885 | (1.04×) |
| RV32IMC | $\mathcal{V}_3$ | | **1157** | 30 | **38610** | **(1.03×)** |
| RV32IMC | $\mathcal{V}_5$ | (L) | 4121 | 22 | 42070 | (1.13×) |
| RV32IMC | $\mathcal{V}_5$ | (A) | 1927 | 23 | 39251 | (1.05×) |
| ISA | Variant | (Goal) | ISE area | ISE Circuit Depth | Rocket + ISE area | |
| RV64IMC | | | | | 3717607 | (1.000×) |
| RV64IMC | $\mathcal{V}_4$ | | 8312 | 27 | 3733786 | (1.004×) |

Table 2: Software implementation metrics (i.e., memory footprint measured in bytes) for each ISE variant.

| ISA | Variant | Enc | Dec | Enc-KeyExp | Dec-KeyExp | .data |
|---|---|---|---|---|---|---|
| RV32IMC | T-table | 804 | 804 | 154 | 174 | 5120 |
| RV32IMC | $\mathcal{V}_1$ | 424 | 424 | **68** | 0 | 10 |
| RV32IMC | $\mathcal{V}_2$ | **234** | **238** | **68** | 62 | 10 |
| RV32IMC | $\mathcal{V}_3$ | 290 | 290 | 86 | 64 | 10 |
| RV32IMC | $\mathcal{V}_5$ | 266 | 278 | 290 | 0 | 10 |
| RV64IMC | $\mathcal{V}_4$ | 268 | 268 | 168 | 100 | 0 |

Table 3: Execution metrics for each ISE variant on the SCARV core. Note that the 64-bit $\mathcal{V}_4$ is absent, since there is no 64-bit SCARV core.

| ISA | Variant | (Goal) | Enc | | Dec | | Enc-KeyExp | | Dec-KeyExp | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | iret | cycles | iret | cycles | iret | cycles | iret | cycles |
| RV32IMC | T-table | | 998 | 1076 | 998 | 1103 | 466 | 554 | 1747 | 2346 |
| RV32IMC | $\mathcal{V}_1$ | (L) | 518 | 593 | 518 | 607 | **198** | **291** | **204** | **310** |
| RV32IMC | $\mathcal{V}_1$ | (A) | 518 | 753 | 518 | 775 | **198** | 331 | **204** | 350 |
| RV32IMC | $\mathcal{V}_2$ | (L) | **221** | 301 | **222** | 303 | **198** | 302 | 335 | 616 |
| RV32IMC | $\mathcal{V}_2$ | (A) | **221** | 538 | **222** | 540 | **198** | 332 | 335 | 754 |
| RV32IMC | $\mathcal{V}_3$ | | 238 | **291** | 238 | **286** | 219 | 312 | 659 | 1118 |
| RV32IMC | $\mathcal{V}_5$ | (L) | 233 | 304 | 233 | 309 | 332 | 447 | 338 | 466 |
| RV32IMC | $\mathcal{V}_5$ | (A) | 233 | 556 | 233 | 550 | 332 | 477 | 338 | 496 |

Table 4: Execution metrics for each ISE variant on the Rocket core. Note that the 64-bit $\mathcal{V}_4$ uses the 64-bit Rocket core; all others use the 32-bit Rocket core.

| ISA | Variant | (Goal) | Enc | | Dec | | Enc-KeyExp | | Dec-KeyExp | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | iret | cycles | iret | cycles | iret | cycles | iret | cycles |
| RV32IMC | T-table | | 948 | 1143 | 949 | 1025 | 444 | 478 | 1726 | 1977 |
| RV32IMC | $\mathcal{V}_1$ | (L) | 528 | 685 | 529 | 680 | **212** | 341 | **214** | **290** |
| RV32IMC | $\mathcal{V}_1$ | (A) | 528 | 804 | 529 | 744 | **212** | 357 | **214** | 335 |
| RV32IMC | $\mathcal{V}_2$ | (L) | **231** | **359** | **233** | 368 | **212** | **315** | 350 | 508 |
| RV32IMC | $\mathcal{V}_2$ | (A) | **231** | 511 | **233** | 520 | 212 | 345 | 350 | 646 |
| RV32IMC | $\mathcal{V}_3$ | | 253 | 445 | 254 | 445 | 233 | 470 | 674 | 2425 |
| RV32IMC | $\mathcal{V}_5$ | (L) | 243 | 414 | 244 | **319** | 346 | 427 | 348 | 424 |
| RV32IMC | $\mathcal{V}_5$ | (A) | 243 | 585 | 244 | 543 | 346 | 504 | 348 | 454 |
| RV64IMC | $\mathcal{V}_4$ | | 81 | 119 | 82 | 125 | 66 | 204 | 136 | 306 |

Table 5: Comparison of improvement per unit-area for each ISE variant.

| ISA | Variant | (Goal) | Enc iret | Enc cycles | Dec iret | Dec cycles | Enc-KeyExp iret | Enc-KeyExp cycles | Dec-KeyExp iret | Dec-KeyExp cycles |
|---|---|---|---|---|---|---|---|---|---|---|
| RV32IMC | $\mathcal{V}_1$ | (L) | 4.61 | 4.34 | 4.61 | 4.35 | 5.39 | 6.06 | 20.50 | 18.12 |
| RV32IMC | $\mathcal{V}_1$ | (A) | 7.37 | 5.46 | 7.37 | 5.44 | 8.61 | 6.40 | **32.74** | **25.63** |
| RV32IMC | $\mathcal{V}_2$ | (L) | 10.58 | 8.38 | 10.53 | 8.53 | 5.28 | 4.30 | 12.22 | 8.92 |
| RV32IMC | $\mathcal{V}_2$ | (A) | 27.18 | 12.04 | 27.06 | 12.29 | 13.56 | 10.04 | 31.39 | 18.73 |
| RV32IMC | $\mathcal{V}_3$ | | **30.12** | **26.56** | **30.12** | **27.71** | **14.63** | **12.76** | 19.04 | 15.08 |
| RV32IMC | $\mathcal{V}_5$ | (L) | 8.64 | 7.14 | 8.64 | 7.20 | 2.71 | 2.50 | 10.43 | 10.15 |
| RV32IMC | $\mathcal{V}_5$ | (A) | 18.48 | 8.35 | 17.64 | 8.30 | 5.79 | 5.01 | 22.29 | 20.40 |
| RV64IMC | $\mathcal{V}_4$ | | 12.32 | 9.04 | 12.17 | 8.82 | 6.76 | 2.72 | 12.85 | 7.67 |

Table 6: Instruction counts for multiplication in $\mathbb{F}_{2^{128}}$ as used by GHASH.

| ISA | Karatsuba | Reduce | `grev` | `xor` | `s[lr]li` | `clmul` | `clmulh` | Total |
|---|---|---|---|---|---|---|---|---|
| RV32IB | no | mul | 4 | 36 | 0 | 20 | 20 | 80 |
| RV32IB | no | shift | 4 | 56 | 24 | 16 | 16 | 116 |
| RV32IB | yes | mul | 4 | 52 | 0 | 13 | 13 | 82 |
| RV32IB | yes | shift | 4 | 72 | 24 | 9 | 9 | 118 |
| RV64IB | no | mul | 2 | 10 | 0 | 6 | 6 | 24 |
| RV64IB | no | shift | 2 | 20 | 12 | 4 | 4 | 42 |
| RV64IB | yes | mul | 2 | 14 | 0 | 5 | 5 | 26 |
| RV64IB | yes | shift | 2 | 24 | 12 | 3 | 3 | 44 |

Table 7: Modelled cycle counts for multiplication in $\mathbb{F}_{2^{128}}$ as used by GHASH.

| ISA | Karatsuba | Reduce | 1-cycle `clmul[h]` | 2-cycle `clmul[h]` | 3-cycle `clmul[h]` | 6-cycle `clmul[h]` |
|---|---|---|---|---|---|---|
| RV32IB | no | mul | **80** | 120 | 160 | 280 |
| RV32IB | no | shift | 116 | 148 | 180 | 276 |
| RV32IB | yes | mul | 82 | **108** | **134** | 212 |
| RV32IB | yes | shift | 118 | 136 | 154 | **208** |
| RV64IB | no | mul | **24** | **36** | 48 | 84 |
| RV64IB | no | shift | 42 | 50 | 58 | 82 |
| RV64IB | yes | mul | 26 | **36** | **46** | 76 |
| RV64IB | yes | shift | 44 | 50 | 56 | **74** |

The Galois/Counter Mode (GCM) [NIS07] is a block cipher mode of operation which supports authenticated encryption. AES-GCM refers to an instantiation using AES as the underlying block cipher, which is the only case mandated by TLS 1.3 [Res18, Section 9.1]; the importance of this construction means GCM and AES are frequently considered together from an implementation and evaluation perspective. The computational core of AES-GCM is formed from two components. GCTR, [NIS07, Section 6.5] is responsible for encryption using AES, and GHASH [NIS07, Section 6.4] is responsible for authentication. Having dealt with efficient implementation of AES and hence GCTR in Section 3, we turn our attention to GHASH. Rather than further embellish the ISE for AES, we instead focus on re-use of the proposed standard Bit-manipulation [RV:19a, Section 17] extension.

**Implementation.** GHASH [NIS07, Section 6.4] is a universal hash defined over the finite field $\mathbb{F}_{2^{128}}$ constructed as $\mathbb{F}_2[\mathbf{x}]/(\mathbf{x}^{128} + \mathbf{x}^7 + \mathbf{x}^2 + \mathbf{x} + 1)$. Conversion of the input into the correct endianness can be realised using the `grev` (or generalised reverse) instruction, which can reverse the bits in each byte of an input word: 4 (resp. 2) `grev` instructions are therefore required on RV32IB (resp. RV64IB). Beyond this, operations in $\mathbb{F}_{2^{128}}$ dominate. Addition in

$\mathbb{F}_{2^{128}}$ is equivalent to XOR: thus 4 (resp. 2) `xor` instructions are required on RV32IB (resp. RV64IB). Multiplication in $\mathbb{F}_{2^{128}}$ can be split into two steps: a $(128 \times 128)$-bit polynomial multiplication, followed by a reduction of the 256-bit result modulo $\mathtt{x}^{128} + \mathtt{x}^7 + \mathtt{x}^2 + \mathtt{x} + 1$. The first step can be realised using pairs of "carry-less" multiplication instructions `clmul` and `clmulh`. These compute the least significant (resp. most-significant) half of a carry-less product (i.e., product over $\mathbb{F}_2$). Pairs of `clmul` and `clmulh` should be scheduled adjacently, allowing capable micro-architectures to fuse them. Use of a school book approach requires 16 (resp. 4) pairs on RV32IB (resp. RV64IB). Optimisation using the Karatsuba method requires 9 (resp. 3) such pairs on RV32IB (resp. RV64IB), plus some additional `xor` instructions. The second step can be implemented in two ways: a shift-based reduction, made possible by the low Hamming weight of the primitive polynomial, or a multiplication-based reduction, analogous to the Montgomery or Barret methods. The most efficient approach depends on the relative execution latency of `clmul[h]` vs. `xor` and `s[lr]li`. Note that the entire GHASH operation, including `clmul[h]`, *must* exhibit data-oblivious execution latency (e.g., avoid data-dependent optimisations like early-termination) to avoid associated side-channel attacks (cf. [GOPT09]).

**Discussion.** Table 6 lists instruction counts for multiplication in $\mathbb{F}_{2^{128}}$, implemented using combinations of the base ISA, and approaches for the polynomial multiplication and reduction steps. Table 7 then models the execution latency (measured in cycles) assuming `grev`, `xor`, and `s[lr]li` take 1 cycle. Although the model only considers an in-order core in line with those used in Section 3 and is focused on execution latency (vs. other pertinent metrics, such as code footprint), there are two obvious conclusions: if `clmul[h]` has 2 (or more) times the latency of `xor` and `s[lr]li`, a Karatsuba polynomial multiplication is preferable. If `clmul[h]` has 6 (or more) times the latency of `xor` and `s[lr]li`, a shift-based reduction is preferable.

The authors recommend the carry-less multiply instructions specified in the proposed RISC-V Bit-manipulation extension also be included in the RISC-V cryptography extension. Implementers would otherwise need to implement (a subset of) the B extension, potentially adding functionality and cost that is not nessesary.

## 5 Hardening an AES ISE against DPA attack

In embedded IoT class devices to which an attacker may have physical access, Differential Power Analysis (DPA) attacks on cryptographic implementations [KJJ99] can be devastating. While ISEs give a notable increase in efficiency, they can also create attractive targets for DPA attacks. This stems from there being only one way to sensibly implement AES using the ISE and the ISE having very well defined behaviour. This reduces the number of target variables or implementation styles an attacker needs to consider. It is then important to consider how an implementer might further extend a cryptographic ISE to secure it against DPA attacks. While our focus here is on DPA attacks, we note that Differential Electro-Magnetic Analysis attacks are exploited and countered using similar techniques to DPA.

Having identified ISE $\mathcal{V}_3$ as a strong standardisation candidate for embedded 32-bit RISC-V cores, we take a hardware/software co-design approach to extending the ISE, adding 1st order DPA side-channel resistance.

### 5.1 Design

We based our design on boolean masking, and represent the secret key as two Boolean masked shares.

An implementation of the AES block encrypt/decrypt function using $\mathcal{V}_3$ requires eight GPRs: four for the current round state and four to load the next round key and then accumulate the next round state. See Figure 13 for an AES round function implementation using $\mathcal{V}_3$. Storing shares of each secret variable in the General Purpose Register (GPR) file is unreasonable, requiring drastic modifications to the instruction definitions and register file to read four registers (two sources, of two shares each) and write two registers. This would break the RISC-V 2-read-1-write principle. Storing corresponding shares in the GPRs is also a security risk, as they may be accidentally combined due to careless instruction use, or implicit register accesses by the CPU micro-architecture.

Instead, we define a new, 8-element "Mask Register File" (MRF). Each mask register $M_i$ is $R = 32$-bits wide, and stores the mask for one of the GPRs. We use a fixed mapping between GPRs and mask registers; not all GPRs have a corresponding mask register. We use the mapping $\{a0..a3, t0..t4\} \Rightarrow \{m0..m7\}$.

Share 0 of each secret value is loaded into the GPRs using the standard RISC-V Load Word (`lw`) instruction. We define a new Load Mask instruction `lm rd, offset(rs1)` which loads *the mask for GPR* `rd` (i.e. Share 1) from memory into the corresponding MRF entry. A corresponding Store Mask instruction `sm rs2, offset(rs1)` writes the mask corresponding to GPR `rs2` to memory. The `sm` instruction is only used for context switches, and destructively reads the MRF register value to prevent it being leaked to other applications running on the same core.[6] We require the secret values be stored in shared form in memory (rather than splitting them into shares upon being loaded) to extend the SCA protection boundary outside the CPU. Otherwise, the hamming weight of unmasked secret values would be leaked by memory-hierarchy registers outside the CPU. Executing an `lm` instruction such that `rd` does not map to a mask register raises an illegal opcode exception. Likewise for `sm` and `rs2`.

When an ISE instruction is executed and its GPR source registers map to an MRF register, both the GPRs and MRF are read simultaneously and fed to the AES functional unit. If any GPR source does not map to an MRF register, we assume that operand is unmasked and represent the other share as 0.

Within the AES-FU the instruction result is computed entirely in a masked representation. The result shares are then re-masked before being written back to the GPRs and MRF. This is necessary, because $\mathcal{V}_3$ instructions are designed such that `rs1=rd` for all use cases. Without re-masking, overwriting a source with the result could cause 1'st order hamming-distance leakage.

If the destination GPR has a corresponding mask register, share 0 is stored in the GPRs and share 1 in the MRF. If the destination GPR does not map to a mask register, the result is written to the GPR unmasked. This means that in the final encrypt/decrypt round, we can optionally obtain the unmasked results without having to store the shares to memory, load them back and unmask them.

## 5.2 Implementation

We used the SCARV core as the basis for our side-channel secure implementation of $\mathcal{V}_3$. Figure 24 shows a block diagram of the modifications made to the core, and which data-paths carry masked data. To avoid accidental unmasking of the two shares, Share 1 is stored in *bit-reversed* form in the MRF and pipeline registers. This means that any accidental multiplexing between pipeline operand registers causes toggles between non-corresponding bits of each share. Share 1 is only un-reversed immediately prior to entering the AES functional unit, and is re-reversed before exiting it. Bit-reversal has zero logic gate cost and some minor routing complexity.

[6] In this case, destructive could mean set to zero (which could leak the hamming weight of the mask) or randomising its value.

While the architectural state stores a 2-share representation of the secret material, we use a 3-share implementation of the AES S-box. This was driven by experiments showing leakage from a 2-share design in our FPGA platform. The additional share is generated by a simple 32-bit LFSR and added dynamically by the hardware, and is never visible to the programmer. This is suitable for a proof of concept (evident in the experimental results) but would need to be used in conjunction with a true random number source (e.g., a set of ring-oscillators) in a deployed system. Only the S-box is implemented using 3-shares. Subsequent `MixColumns` logic is only implemented using 2 shares.

## 5.3 Evaluation

The modified SCARV core was implemented on a Sasebo GIII [HKSS12] side-channel analysis platform, containing two Xilinx FPGAs: a Kintex-7 (model `xc7k160tfbg676`) target and a supporting Spartan-6 (model `xc6slx45`). Only the Kintex-7 was used. The design was synthesised using Xilinx Vivado 2019.2 with default synthesis and implementation strategies. The Kintex-7 FPGA uses a 200MHz differential external clock source, which is transformed into a 50MHz internal clock used by the entire design.

Trace capture uses a standard pipeline of components: a MiniCircuits BLK+89 D/C blocker, an Agilent 8447D amplifier (with a 100 kHz to 1.3 GHz range, and 25 dB gain), and a PicoScope 5000 series oscilloscope using a 250 MHz sample rate, with a 12-bit resolution.

We performed a generic randomised plaintext Test Vector Leakage Assessment (TVLA) [CDG+13] flow to evaluate the effectiveness of the side-channel hardened implementation, using the AES-128 block encrypt function as the target operation. The unprotected and protected implementation results are shown in Figure 2a and Figure 2b respectively. The protected implementation is effective at removing 1st order side-channel leakage up to 100K traces. The peaks at the beginning and end of Figure 2b are caused by the unmasked block input and output data being loaded/stored.

Table 8 shows the hardware and software overheads. The ISE Size/Circuit Depth rows are inclusive of the S-box Size/Circuit Depth rows. Likewise, the CPU Size rows are inclusive of the ISE Size rows. The static code size and instruction count overheads are $\approx 20\%$: considerably less than a non-ISE-based software masking approach. The hardware overheads are dominated by the increased size of the S-box (owing to the 3-share design), and the MRF. Although the overhead to the dedicated ISE logic is  $4x$, this drops to $1.2x$ when the entire CPU sub-system is considered. Measured against an entire SoC, the overheads are modest.

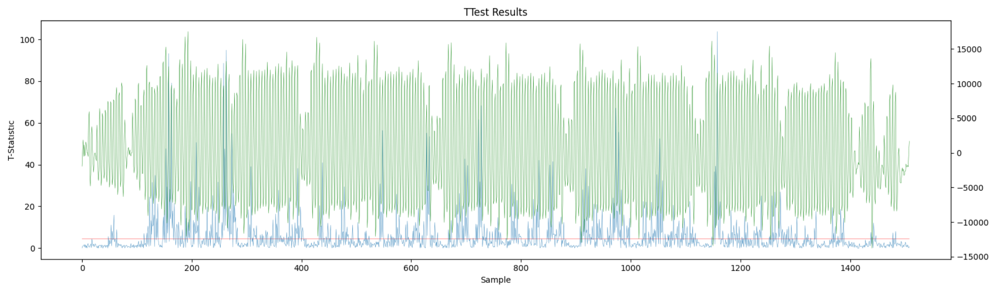
## 6 Conclusion

Although differing in nature, both AES and RISC-V represent important standards. In this paper, we have addressed the challenge of secure, efficient implementation of AES on RISC-V: our approach harnesses the modularity afforded by RISC-V, through a focus on the use of ISEs.

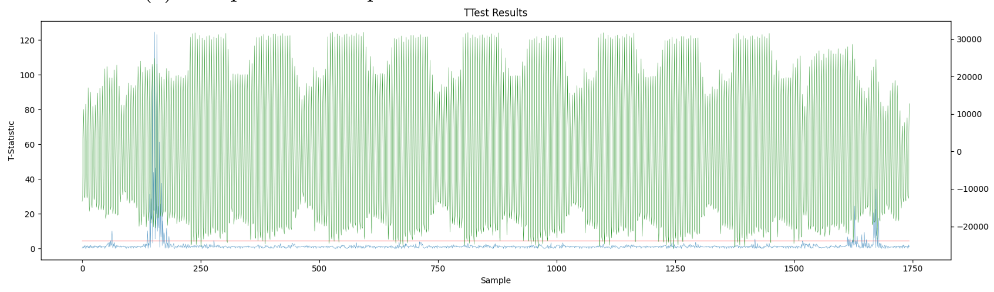
Specifically, and motivated by ongoing efforts to standardise support for AES in RISC-V, we have implemented and evaluated five ISE designs on two different RISC-V compliant base micro-architectures. Our conclusion is that 1) $\mathcal{V}_3$ is the best option for AES on 32-bit cores, 2) $\mathcal{V}_4$ is the best option for AES on 64-bit cores, and 3) the standard B [RV:19a, Section 17] extension can combine with either option to support AES-GCM. Furthermore, we demonstrated that, with reasonable alterations to the base micro-architecture, our implementation of $\mathcal{V}_3$ can be hardened (via masking) to prevent 1st order DPA-style attacks.

Table 8: Software and hardware overheads for the protected ISE implementation of AES-128 block encryption. The "ISE Size" row does not include the cost of the mask register file for the protected implementation; this is included in the CPU size measurements, since the exact method of mask delivery and storage is an implementation option.

| Metric | Unprotected | Protected | Overhead |
|---|---|---|---|
| Static Code Size (Bytes) | 290 | 358 | 1.23× |
| Instructions Executed | 238 | 287 | 1.21× |
| CPU Clock Cycles | 291 | 331 | 1.14× |
| S-box Size (NAND2 Equivalent) | 554 | 3245 | 5.86× |
| S-box Circuit Depth | 19 | 22 | 1.16× |
| ISE Size (NAND2 Equivalent) | 1157 | 4616 | 3.99× |
| ISE Circuit Depth | 30 | 37 | 1.23× |
| CPU Size (NAND2 Equivalent) | 38610 | 45141 | 1.16× |
| CPU Size LUTs | 4017 | 4956 | 1.23× |
| CPU Size FFs | 2078 | 2420 | 1.16× |
| FPGA Timing Slack @50MHz | 8.12ns | 7.05ns | 0.87× |



(a) Un-protected implementation TVLA results after 10K traces.



(b) Side-channel protected implementation TVLA results after 100K traces.

Figure 2: TVLA results for the baseline and protected implementations. The blue trace is the absolute result of the TVLA evaluation, the green trace is the average power consumption for each TVLA trace set.

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# A $\mathcal{V}_1$: additional technical detail

```
saes.v1.encs rd, rs1 : v1.SubBytes(rd, rs1, fwd=1)
saes.v1.decs rd, rs1 : v1.SubBytes(rd, rs1, fwd=0)
saes.v1.encm rd, rs1 : v1.MixColumn(rd, rs1, fwd=1)
saes.v1.decm rd, rs1 : v1.MixColumn(rd, rs1, fwd=0)
```

Figure 3: Instruction mnemonics, and their mapping onto pseudo-code functions, for $\mathcal{V}_1$.

```
v1.SubByte(rd, rs1, fwd):
    rd.8[i] = AESSBox[rs1.8[i]] if fwd else AESInbSBox[rs1.8[i]] for i=0..3

v1.MixColumn(rd, rs1, fwd)
    for i=0..3:
        tmp.32  = ROTL32(rs1.32, 8*i)
        rd.8[i] = AESMixColumn(tmp.32) if fwd else AESInvMixColumn(tmp.32)
```

Figure 4: Instruction pseudo-code functions for $\mathcal{V}_1$.

```
lw           a0,  0(a4)       // Load Round Key
lw           a1,  4(a4)
lw           a2,  8(a4)
lw           a3, 12(a4)
xor          a4, a4, a0       // Add Round Key
xor          a5, a5, a1
xor          a6, a6, a2
xor          a7, a7, a3
saes.v1.encs a0, a4           // SubBytes
saes.v1.encs a1, a5
saes.v1.encs a2, a6
saes.v1.encs a3, a7
                              // Shift Rows
and          a4, t0, t6   ; and   a5, t1, t6
and          a6, t2, t6   ; and   a7, t3, t6
slli         t4, t6, 0x8  ; and   t5, t0, t4
or           a7, a7, t5   ; and   t5, t3, t4
or           a6, a6, t5   ; and   t5, t2, t4
or           a5, a5, t5   ; and   t5, t1, t4
or           a4, a4, t5   ; slli  t4, t4, 0x8
and          t5, t2, t4   ; or    a4, a4, t5
and          t5, t3, t4   ; or    a5, a5, t5
and          t5, t0, t4   ; or    a6, a6, t5
and          t5, t1, t4   ; or    a7, a7, t5
slli         t4, t4, 0x8  ; and   t5, t3, t4
or           a4, a4, t5   ; and   t5, t0, t4
or           a5, a5, t5   ; and   t5, t1, t4
or           a6, a6, t5   ; and   t5, t2, t4
or           a7, a7, t5
saes.v1.encm t0, a4           // MixColumns
saes.v1.encm t1, a5
saes.v1.encm t2, a6
saes.v1.encm t3, a7
```

Figure 5: An AES encryption round implemented using $\mathcal{V}_1$.

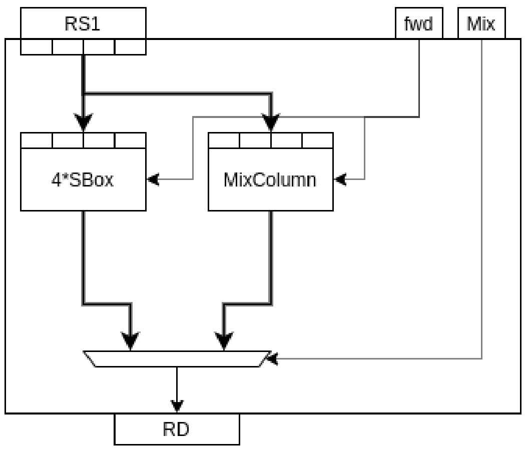

Figure 6: A diagrammatic description of the functional unit required to support $\mathcal{V}_1$.

## B $\mathcal{V}_2$: additional technical detail

```
saes.v2.encs rd, rs1, rs2 : v2.SubBytes(rd, rs1, rs2, fwd=1)
saes.v2.decs rd, rs1, rs2 : v2.SubBytes(rd, rs1, rs2, fwd=0)
saes.v2.encm rd, rs1, rs2 : v2.MixColumns(rd, rs1, rs2, fwd=1)
saes.v2.decm rd, rs1, rs2 : v2.MixColumns(rd, rs1, rs2, fwd=0)
```

Figure 7: Instruction mnemonics, and their mapping onto pseudo-code functions, for $\mathcal{V}_2$.

```
v2.SubBytes(rd, rs1, rs2, fwd):
  t1.32  = {rs1.8[0], rs2.8[1], rs1.8[2], rs2.8[3]}
  rd.8[i]= AESSBox[t1.8[i]] if fwd else AESInvSBox[t1.8[i]] for i=0..3

v2.MixColumns(rd, rs1, rs2, fwd):
  t1.32  = {rs1.8[0], rs1.8[1], rs2.8[2], rs2.8[3]}
  for i=0..3:
      tmp.32 = ROTL32(rs1.32, 8*i)
      rd.8[i]= AESMixColumn(tmp.32) if fwd else AESInvMixColumn(tmp.32)
```

Figure 8: Instruction pseudo-code functions for $\mathcal{V}_2$.

```
lw              a0,  0(a4)     // Load Round Key
lw              a1,  4(a4)
lw              a2,  8(a4)
lw              a3, 12(a4)
xor             t0, t0, a0     // Add Round Key
xor             t1, t1, a1
xor             t2, t2, a2
xor             t3, t3, a3
saes.v2.sub.enc a0, t0, t1     // SubBytes / ShiftRows
saes.v2.sub.enc a1, t2, t3
saes.v2.sub.enc a2, t1, t2
saes.v2.sub.enc a3, t3, t0
saes.v2.mix.enc t0, a0, a1     // ShiftRows / MixColumns
saes.v2.mix.enc t1, a2, a3
saes.v2.mix.enc t2, a1, a0
saes.v2.mix.enc t3, a3, a2
```

Figure 9: An AES encryption round implemented using $\mathcal{V}_2$.

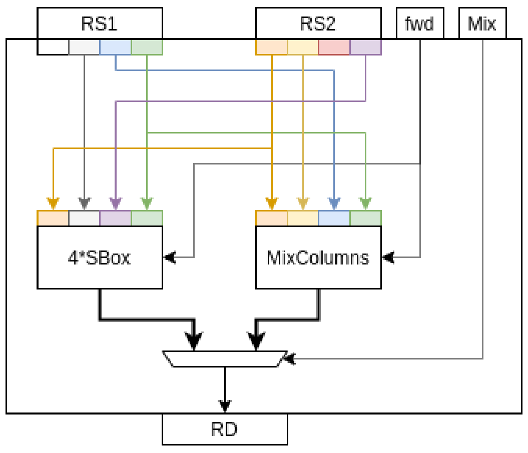

Figure 10: A diagrammatic description of the functional unit required to support $\mathcal{V}_2$.

## C $\mathcal{V}_3$: additional technical detail

```
saes.v3.encs  rd, rs1, rs2, bs : v3.Proc(rd, rs1, rs2, bs, fwd=1, mix=0)
saes.v3.encsm rd, rs1, rs2, bs : v3.Proc(rd, rs1, rs2, bs, fwd=1, mix=1)
saes.v3.decs  rd, rs1, rs2, bs : v3.Proc(rd, rs1, rs2, bs, fwd=0, mix=0)
saes.v3.decsm rd, rs1, rs2, bs : v3.Proc(rd, rs1, rs2, bs, fwd=0, mix=1)
```

Figure 11: Instruction mnemonics, and their mapping onto pseudo-code functions, for $\mathcal{V}_3$.

```
v3.Proc(rd, rs1, rs2, bs, fwd, mix):
  x     = AESSBox[rs2.8[bs]] if fwd else AESInvSBox[rs2.8[bs]]
  if   mix and  fwd: t1.32 = {GFMUL(x, 3),      x     ,      x    ,GFMUL(x, 2)}
  elif mix and !fwd: t1.32 = {GFMUL(x,11),GFMUL(x,13),GFMUL(x,9),GFMUL(x,14)}
  else             : t1.32 = {0, 0, 0, x}
  rd.32 = ROTL32(t1.32, 8*bs) ^ rs1
```

Figure 12: Instruction pseudo-code functions for $\mathcal{V}_3$.

```
lw               a0, 16(RK)       // Load Round Key
lw               a1, 20(RK)
lw               a2, 24(RK)
lw               a3, 28(RK)       // t0,t1,t2,t3 contains current round state.
saes.v3.encsm    a0, a0, t0, 0    // Next state for column 0.
saes.v3.encsm    a0, a0, t1, 1    // Current column 0 in t0.
saes.v3.encsm    a0, a0, t2, 2    // Next column 0 accumulates in a0
saes.v3.encsm    a0, a0, t3, 3
saes.v3.encsm    a1, a1, t1, 0    // Next state for column 1.
saes.v3.encsm    a1, a1, t2, 1
saes.v3.encsm    a1, a1, t3, 2
saes.v3.encsm    a1, a1, t0, 3
saes.v3.encsm    a2, a2, t2, 0    // Next state for column 2.
saes.v3.encsm    a2, a2, t3, 1
saes.v3.encsm    a2, a2, t0, 2
saes.v3.encsm    a2, a2, t1, 3
saes.v3.encsm    a3, a3, t3, 0    // Next state for column 3.
saes.v3.encsm    a3, a3, t0, 1
saes.v3.encsm    a3, a3, t1, 2
saes.v3.encsm    a3, a3, t2, 3    // a0,a1,a2,a3 contains new round state
```

Figure 13: An AES encryption round implemented using $\mathcal{V}_3$.

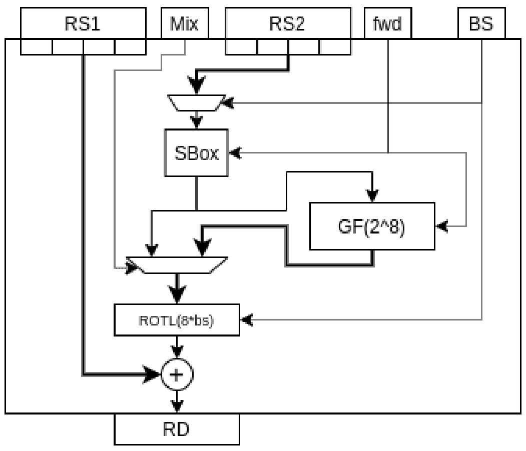

Figure 14: A diagrammatic description of the functional unit required to support $\mathcal{V}_3$.

## D $\mathcal{V}_4$: additional technical detail

```
saes.v4.ks1        rd rs1 rcon : v4.ks1(rd, rs1, rcon)
saes.v4.ks2        rd rs1 rs2  : v4.ks2(rd, rs1, rs2 )
saes.v4.imix       rd rs1      : v4.InvMix(rd, rs1)
saes.v4.encsm      rd rs1 rs2  : v4.Enc(rd, rs1, rs2, mix=1)
saes.v4.encs       rd rs1 rs2  : v4.Enc(rd, rs1, rs2, mix=0)
saes.v4.decsm      rd rs1 rs2  : v4.Dec(rd, rs1, rs2, mix=1)
saes.v4.decs       rd rs1 rs2  : v4.Dec(rd, rs1, rs2, mix=0)
```

Figure 15: Instruction mnemonics, and their mapping onto pseudo-code functions, for $\mathcal{V}_4$.

```
v4.ks1(rd, rs1, enc_rcon):      // KeySchedule: SubBytes, Rotate, Round Const
    temp.32    = rs1.32[1]
    rcon       = 0x0
    if(enc_rcon != 0xA):
        temp.32 = ROTR32(temp.32, 8)
        rcon    = RoundConstants.8[enc_rcon]
    temp.8[i] = AESSBox[temp.8[i]]  for i=0..3
    temp.8[0] = temp.8[0] ^ rcon
    rd.64     = {temp.32, temp.32}

v4.ks2(rd, rs1, rs2):           // KeySchedule: XOR
    rd.32[0]  = rs1.32[1] ^ rs2.32[0]
    rd.32[1]  = rs1.32[1] ^ rs2.32[0] ^ rs2.32[1]

v4.Enc(rd, rs1, rs2, mix): // SubBytes, ShiftRows, MixColumns
    t1.128    = ShiftRows({rs2, rs1})
    t2.64     = t1.64[0]
    t3.8[i]   = AESSBox[t2.8[i]] for i=0..7
    rd.32[i]  = AESMixColumn(t3.32[i]) if mix else t3.32[i] for i=0..1

v4.Dec(rd, rs1, rs2, mix, hi): // InvSubBytes, InvShiftRows, InvMixColumns
    t1.128    = InvShiftRows(rs2 || rs1)
    t2.64     = t1.64[0]
    t3.8[i]   = AESInvSBox[t2.8[i]] for i=0..7
    rd.32[i]  = AESInvMixColumn(t3.32[i]) if mix else t3.32[i] for i=0..1

v4.InvMix(rd, rs1):             // Inverse MixColumns
    rd.32[i]  = AESInvMixColumn(rs1.32[i]) for i=0..1
```

Figure 16: Instruction pseudo-code functions for $\mathcal{V}_4$.

```
ld             a0, 0(a4)  // Load round key as double words.
ld             a1, 8(a4)
xor            t0, t0, a0 // Add round key for 2 columns at a time.
xor            t1, t1, a1
aes.v5.encsm   t2, t0, t1 // Next round state: columns 0, 1
aes.v5.encsm   t3, t1, t0 // columns 2, 3 - Note swapped rs1/rs2
```

Figure 17: An AES encryption round implemented using $\mathcal{V}_4$.

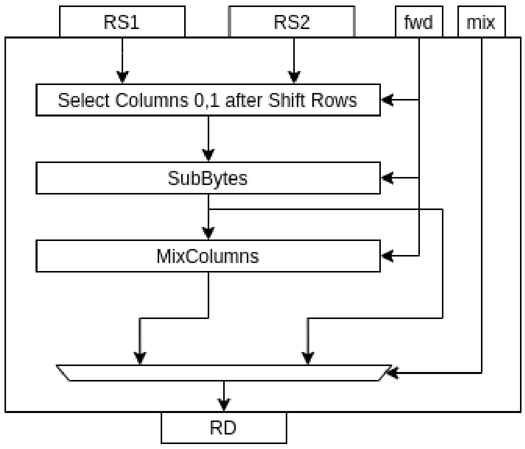

Figure 18: A diagrammatic description of the functional unit required to support the $\mathcal{V}_4$ round instructions.

# E $\mathcal{V}_5$: additional technical detail

```
saes.v5.esrsub.lo rd, rs1, rs2 : rd = v5.SrSub(rs1, rs2, fwd=1, hi=0)
saes.v5.esrsub.hi rd, rs1, rs2 : rd = v5.SrSub(rs1, rs2, fwd=1, hi=1)
saes.v5.dsrsub.lo rd, rs1, rs2 : rd = v5.SrSub(rs1, rs2, fwd=0, hi=0)
saes.v5.dsrsub.hi rd, rs1, rs2 : rd = v5.SrSub(rs1, rs2, fwd=0, hi=1)
saes.v5.emix      rd, rs1, rs2 : rd = v5.Mix(rs1, rs2, fwd=1)
saes.v5.dmix      rd, rs1, rs2 : rd = v5.Mix(rs1, rs2, fwd=0)
saes.v5.sub       rd, rs1      : rd = SubBytes(rs1.8[i])         for i=0..3
```

Figure 19: Instruction mnemonics, and their mapping onto pseudo-code functions, for $\mathcal{V}_5$.

```
v5.SrSub(rd, rs1, rs2, fwd, hi):
  if(fwd):
    if hi: tmp.32 = {rs1.8[3], rs2.8[0], rs2.8[1], rs2.8[2]}
    else : tmp.32 = {rs2.8[3], rs1.8[1], rs1.8[0], rs1.8[2]}
    tmp.8[i]      =    AESSBox[tmp.8[i]] for i=0..3
  else:
    if hi: tmp.32 = {rs2.8[3], rs2.8[0], rs1.8[1], rs2.8[2]}
    else : tmp.32 = {rs1.8[3], rs2.8[1], rs1.8[0], rs1.8[2]}
    tmp.8[i]      = InvAESSBox[tmp.8[i]] for i=0..3
  if(hi): rd.32 = {tmp.8[2],tmp.8[3],tmp.8[0],tmp.8[1]}
  else  : rd.32 = {tmp.8[1],tmp.8[3],tmp.8[0],tmp.8[2]}

v5.mix(rd, rs1, rs2, fwd):
  col0.32 = {rs1.8[2], rs1.8[3], rs2.8[2], rs2.8[3]}
  col1.32 = {rs1.8[0], rs1.8[1], rs2.8[0], rs2.8[1]}
  n0.8    = AESMixColumn(       col0    ) if fwd else AESInvMixColumn(       col0    )
  n1.8    = AESMixColumn(ROTL32(col0,8)) if fwd else AESInvMixColumn(ROTL32(col0,8))
  n2.8    = AESMixColumn(       col1    ) if fwd else AESInvMixColumn(       col1    )
  n3.8    = AESMixColumn(ROTL32(col1,8)) if fwd else AESInvMixColumn(ROTL32(col1,8))
  rd.32 = {n2, n3, n0, n1}
```

Figure 20: Instruction pseudo-code functions for $\mathcal{V}_5$.

```
lw                a0,  0(a4)   // Load Round Key
lw                a1,  4(a4)
lw                a2,  8(a4)
lw                a3, 12(a4)
xor               t0, t0, a0   // Add Round Key
xor               t1, t1, a1
xor               t2, t2, a2
xor               t3, t3, a3
saes.v5.esrsub.lo a0, t0, t1   // Quad 0: SubBytes / ShiftRows
saes.v5.esrsub.lo a1, t1, t0   // Quad 1
saes.v5.esrsub.hi a2, t2, t3   // Quad 2
saes.v5.esrsub.hi a3, t3, t2   // Quad 3
saes.v5.emix      t0, a0, a2   // Quad 0: ShiftRows / MixColumns
saes.v5.emix      t1, a1, a3   // Quad 1
saes.v5.emix      t2, a2, a0   // Quad 2
saes.v5.emix      t3, a3, a1   // Quad 3
```

Figure 21: An AES encryption round implemented using $\mathcal{V}_5$.

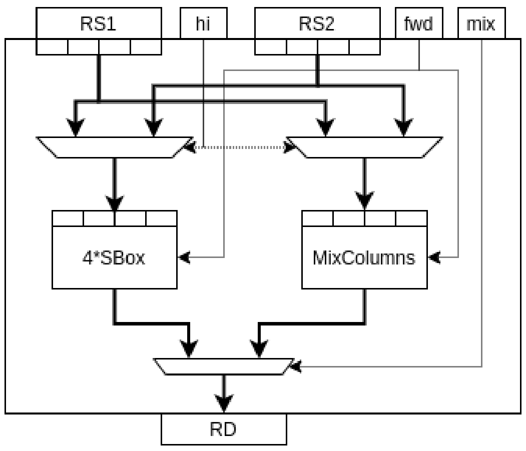

Figure 22: A diagrammatic description of the functional unit required to support $\mathcal{V}_5$.

## F SCARV core: additional technical detail

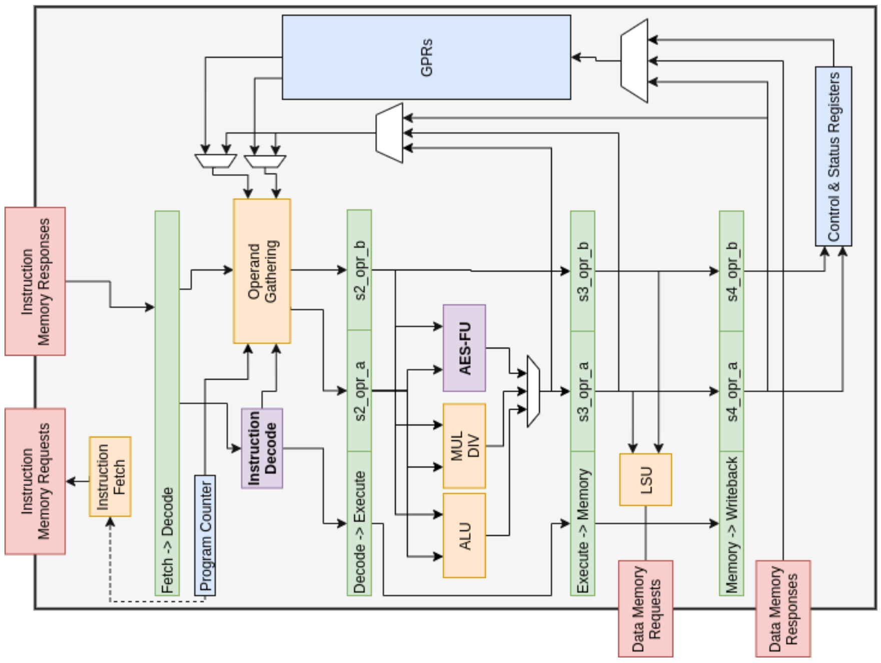

Figure 23: SCARV core: vanilla micro-architecture.

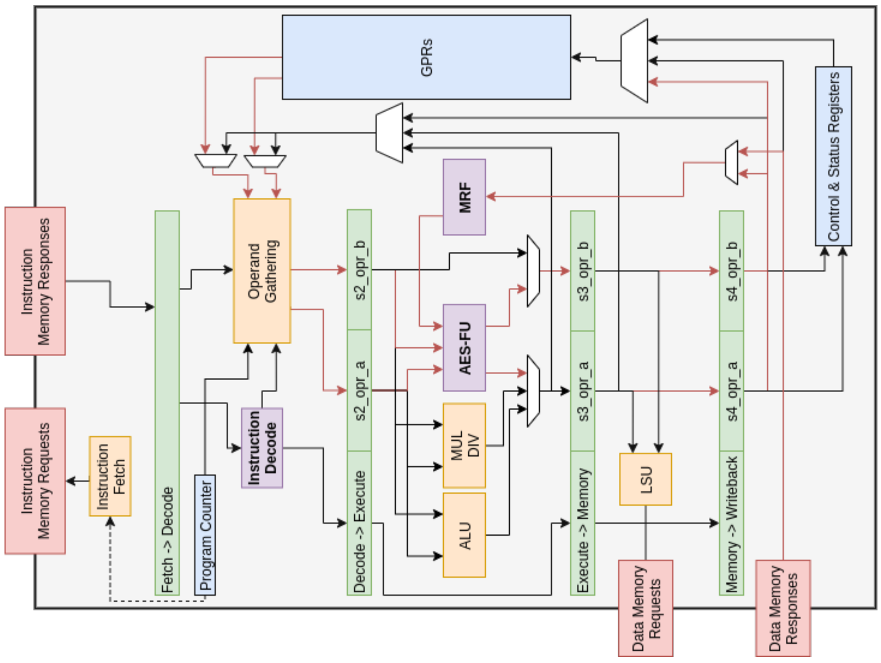

Figure 24: SCARV core: hardened micro-architecture, extending $\mathcal{V}_3$ for improved security against side-channel attack. Connections coloured red are security-critical, in the sense they relate to masks.

## G Rocket core: additional technical detail

```
class AESVanilla32 extends Config (
  new freechips.rocketchip.subsystem.WithNoMMIOPort ++
  new freechips.rocketchip.subsystem.WithNoSlavePort ++
  new freechips.rocketchip.subsystem.WithInclusiveCache ++
  new freechips.rocketchip.subsystem.WithRV32 ++
  new freechips.rocketchip.subsystem.WithNExtTopInterrupts(0) ++
  new freechips.rocketchip.subsystem.WithNBigCores(1) ++
  new freechips.rocketchip.subsystem.WithoutFPU ++
  new freechips.rocketchip.system.BaseConfig
)
```

Figure 25: 32-bit Rocket core configuration.

```
class AESVanilla64 extends Config(
  new freechips.rocketchip.subsystem.WithNoMMIOPort ++
  new freechips.rocketchip.subsystem.WithNoSlavePort ++
  new freechips.rocketchip.subsystem.WithInclusiveCache ++
  new freechips.rocketchip.subsystem.WithNExtTopInterrupts(0) ++
  new freechips.rocketchip.subsystem.WithNBigCores(1) ++
  new freechips.rocketchip.subsystem.WithoutFPU ++
  new freechips.rocketchip.system.BaseConfig
)
```

Figure 26: 64-bit Rocket core configuration.