

Robust Authenticated-Encryption

AEZ and the Problem that it Solves

Viet Tung Hoang^{1,2} Ted Krovetz³ Phillip Rogaway^{4,5}

¹ Dept. of Computer Science, University of Maryland, College Park, USA

² Dept. of Computer Science, Georgetown University, USA

³ Dept. of Computer Science, California State University, Sacramento, USA

⁴ Dept. of Computer Science, University of California, Davis, USA

⁵ Dept. of Computer Science, ETH Zürich, Switzerland

October 4, 2014

Abstract. With a scheme for *robust* authenticated-encryption a user can select an arbitrary value $\lambda \geq 0$ and then encrypt a plaintext of any length into a ciphertext that's λ characters longer. The scheme must provide all the privacy and authenticity possible for the requested λ . We formalize and investigate this idea, and construct a well-optimized solution, AEZ, from the AES round function. Our scheme encrypts strings at almost the same rate as OCB-AES or CTR-AES (on Haswell, AEZ has a peak speed of about 0.7 cpb). To accomplish this we employ an approach we call *accelerated* provable security: the scheme is designed and proven secure in the provable-security tradition, but, to improve speed, one instantiates by scaling down most instances of the underlying primitive.

Keywords: AEZ, arbitrary-input blockciphers, authenticated encryption, robust AE, misuse resistance, nonce reuse, CAESAR competition, blockcipher modes, provable security, symmetric encryption.

Table of Contents

1	Introduction	1
2	Prior AE Definitions	4
3	RAE Security	6
4	Verified Redundancy Enhances Authenticity	8
5	Robust AE from a Generalized Blockcipher	9
6	Wide-Block Enciphering: AEZ-core	10
7	Definition of AEZ	12
8	Security of $\text{AEZ}[\tilde{E}]$ and $\text{AEZ}[E]$	16
9	Estimated Security of AEZ Itself	17
10	Software Performance	18
	Acknowledgments	18
	References	19
A	More on Related Work	21
B	Deferred Proofs	22
	B.1 Proof of Theorem 1	22
	B.2 Proof of Theorem 2	23
	B.3 Proof of Theorem 3	24
	B.4 Proof of Theorem 4	24
	B.5 Proof of Theorem 5	29
	B.6 Proof of Theorem 6	30
C	Tweaking a Wide-Block Blockcipher	30
D	An Insecure Variant of AEZ-core	33

1 Introduction

We expose the low cost and high benefit of building authenticated-encryption (AE) schemes that achieve an unprecedentedly strong goal—what we call *robust* AE (henceforth RAE). We explain why RAE is desirable, define its syntax and security, and explore its guarantees. Then we construct an RAE scheme, AEZ, from AES4 and AES10 (four- and ten-round AES). AEZ’s efficiency—nearly that of OCB [34] or AES-CTR—flies in the face of a community’s collective work [5, 12–14, 20, 26–28, 36, 39–41, 52–54, 61] in which wide-block enciphering schemes—a special case of RAE—were always far more expensive than conventional blockciphers. Achieving this efficiency has entailed using a design paradigm, *accelerated* provable security, with implications beyond AE.

CIPHERTEXT EXPANSION. One can motivate RAE from a syntactic point of view. Recall that in a nonce-based AE scheme, a plaintext M is mapped to a ciphertext $C = \mathcal{E}_K^{N,A}(M)$ under the control of a key K , nonce N , and associated data (AD) A . Typically the *ciphertext expansion* (or *stretch*) $\lambda = |C| - |M|$ is a constant or user-selectable parameter. For conventional AE, the stretch mustn’t be too small, as customary definitions would break: a trivial adversary can get large advantage. This is because AE definitions “give up” when the first forgery occurs. The issue isn’t *only* definitional: no prior AE scheme provides a desirable security guarantee when the ciphertext expansion is small.

Still, we know that strong security is possible even for zero-stretch: a strong pseudorandom permutation buys significant security, even from an AE point of view [6]. What is more, it would seem to be *useful* to allow small stretch as, for example, short tags can save significant energy in resource-constrained environments (as discussed, eg, by Struik [59]).

RAE takes a liberal approach towards ciphertext expansion, accommodating whatever stretch a user requests. This leads to schemes that deliver more than conventional AE even when the stretch is not small. Indeed we could have motivated RAE without considering small- λ , describing a desire to achieve nonce-reuse misuse resistance [51], to automatically exploit novelty or redundancy in plaintexts [6], or to accommodate the release of unverified plaintexts [1, 24]. But our ideas are most easily understood by asking what it means, and what it takes, to do well for any stretch.

DEFINING RAE. So consider an AE scheme that expands a plaintext $M \in \{0,1\}^*$ by a user-selectable number of bits⁶ $\tau \geq 0$. We ask: what’s the best privacy and authenticity guarantee possible for some arbitrary, specified τ ? Robust AE formalizes an answer.

Recall Rogaway and Shrimpton’s definition of a *pseudorandom-injection* (PRI) [51]: for each nonce N and associated data A , for a fixed $\tau \geq 0$, the scheme’s encryption algorithm should resemble a uniformly chosen injective function $\pi_{N,A,\tau}$ from binary strings to τ -bit longer ones. Decryption of an invalid ciphertext (one lacking a preimage under π) should return an indication of invalidity.

PRIs were introduced as an alternative characterization of nonce-reuse misuse-resistant AE (henceforth MRAE). But PRIs only approximate MRAE schemes with large stretch. We recast the PRI notion as prescriptive: the user selects $\tau \geq 0$ and then the scheme must look like a PRI for the chosen value. This is our basic definition for RAE.

RAE can be thought of as a bridge connecting blockciphers and AE. When $\tau=0$ an RAE scheme is an *arbitrary-input blockcipher*: a tweakable blockcipher (TBC) [35] that operates on messages and tweaks of any length and is secure as strong (CCA-secure) pseudorandom permutation (PRP).

⁶ We’ll later permit arbitrary alphabets. To avoid confusion, we use λ to measure ciphertext expansion in *characters* (bits, bytes, etc.—the alphabet arbitrary) and τ to measure it in *bits*.

The nonce, AD, and stretch comprise the tweak. On the other hand, when $\tau \gtrsim 128$ an RAE scheme amounts to an MRAE scheme.

In defining RAE we are actually a bit more generous than what was sketched above, allowing an RAE’s decryption algorithm to return information about an invalid ciphertexts beyond a single-valued indication of invalidity. The information just needs to be harmless. To formalize this the reference experiment uses a simulator S to provide responses to invalid decryption queries. It must do this without benefit of the family of random injections π .

ENCIPHERING-BASED AE. We can achieve RAE with *enciphering-based AE*. The idea, rooted in folklore, was formalized by Bellare and Rogaway [6] and, in a different form, by Shrimpton and Terashima [56]. In its modern incarnation, enciphering-based AE works like this:

Take the message you want to encrypt, augment it with τ -bits of redundancy, and then encipher the resulting string by applying an arbitrary-input blockcipher. Tweak this using the nonce, AD, and an encoding of τ . On decryption, check for the presence of the anticipated redundancy and reject the ciphertext if it’s not there.

We will prove that this method achieves RAE. In fact, we’ll prove that this is so even if the decryption algorithm releases candidate plaintexts with incorrect redundancy.

AEZ. We construct a highly optimized RAE scheme, AEZ. We use the same name to refer to the arbitrary-input blockcipher from which it’s built (using the strategy just described).⁷ With the increasing ubiquity of hardware AES support, we choose to base AEZ on the AES round function.

AEZ attends to the length of its input; see Fig. 1. To encipher a plaintext of fewer than 32 bytes we use AEZ-tiny, a balanced-Feistel scheme with a round function based on AES4, a four-round version of AES. The construction builds on FFX [7, 18]. The more interesting case, AEZ-core, is used to encipher strings of 32 bytes or more. It builds on EME [25, 27] and OTR [37]. Look ahead to the top-left panel of Fig. 7. There are two enciphering layers, with consecutive pairs of blocks processed together using a two-round Feistel network. The round function for this is again based on AES4. The mask injected as the middle layer is determined, for each pair of consecutive blocks, using another AES4 call.

PERFORMANCE. AEZ-core is remarkably fast; as the description above already implies, we need about five AES4 calls to encipher each consecutive pair of blocks, so ten AES rounds per block. Thus our performance approaches that of AES-CTR. An implementation of AEZ on Haswell using AES-NI has a peak speed of 0.72 cpb—about the same as OCB [34]. Look ahead to Fig. 8. Additionally, invalid strings can be rejected, and AD processed, in about 0.4 AES calls per block, or 0.29 cpb peak (again on Haswell). Only the forward direction of AES is used, saving chip area in hardware realizations. The context size, about 128 bytes, is small, and key-setup, about 1.2 AES calls for a 128-bit key, is fast.

For a two-pass mode achieving MRAE, this cluster of performance characteristics is unexpected. Part of the explanation as to how this is possible lies in the use of a design approach that benefits from both classical and provable-security design. Let us explain.

ACCELERATED PROVABLE SECURITY. We designed AEZ using an approach we call *accelerated provable security*. It works like this:

To achieve some complex cryptographic goal, design a scheme in the provable-security tradition, choosing an underlying primitive and demonstrably achieving the goal when it’s instantiated by an object achieving

⁷ Since an RAE scheme *is* an arbitrary-input tweakable blockcipher when $\tau = 0$, and is trivially built from one when $\tau > 0$, it makes sense to use one name.

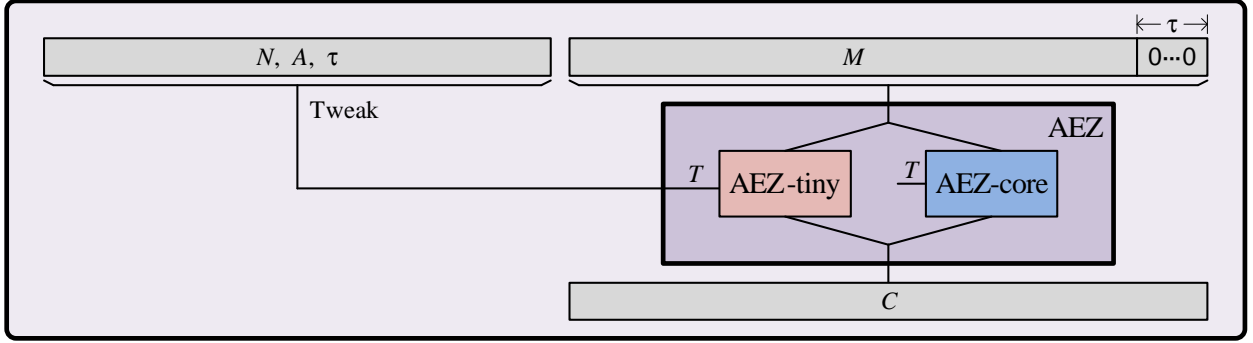


Fig. 1. High-level structure of AEZ. After appending to the message a block of τ zero bits we encipher it using a tweak T comprising the nonce N , associated data A , and stretch τ . How this happens depends on the length of what’s being enciphered: usually we use AEZ-core, but strings shorter than 32 bytes are enciphered by AEZ-tiny. Both depend on the underlying key K , which is not shown in the diagram above.

some standard assumption. Then, to improve speed, selectively instantiate some of the applications of the primitive using a *scaled-down* (eg, reduced-round) construction. Use heuristic or cryptanalytic reasons to support the expectation that, despite the scaled-down instantiation, the scheme remains secure.

Specifically, AEZ is designed in terms of a tweakable blockcipher (TBC). If this TBC had been instantiated in the “usual” way, using a blockcipher and the XE construction [35, 49], we would have a provably-sound design on message space $\{0, 1\}^{\geq 128}$. The cost would be about 2.5 times the cost of AES-CTR. But to speed things up, we instantiate most TBC calls with an AES4-based construction. Heuristics reasons suggest that security nonetheless remains. Our design was specifically chosen so as to make the scaled-down instantiation plausible.

The *thesis* underlying accelerated provable security is that it can be instrumental for devising highly efficient schemes for complex aims. We believe that *if* the instantiation is done judiciously, then the scaled-down scheme retains at least *some* assurance benefit.

Accelerated provable-security is in some ways implicit in prior work; schemes like ALRED [15] typify a trend in which reduced-round AES is used in contexts where full AES would demonstrably do the job. Still, a complex design has not before been achieved by the strategy described.

RAE BENEFITS. What do we hope to gain by developing and achieving RAE? Our definition and scheme are meant to achieve all of the following: (1) If (M, A) tuples are known *a priori* not to repeat, no nonce is needed to ensure semantic security. (2) If there’s arbitrary redundancy in plaintexts whose presence is verified on decryption, this augments authenticity. (3) Any authenticator-length can be selected, achieving best-possible authenticity for this amount of stretch. (4) Because of the last two properties, one can minimize length-expansion in many bandwidth-constrained applications. (5) If what’s supposed to be a nonce should accidentally get repeated, the privacy loss is limited to revealing repetitions in (N, A, M) tuples, while authenticity is not damaged at all. (6) If a decrypting party leaks some or all of a putative plaintext that was supposed to be squelched because of an authenticity-check failure, this won’t compromise privacy or authenticity.

The authors believe that the properties enumerated would sometimes be worth a considerable computational price. Yet the overhead we pay is very small: AEZ is about as fast as OCB.

DISCUSSION. AEZ’s name is meant to simultaneously suggest AE, AES, and EZ (easy), the last in the sense of ease of correct use. But the simplicity is for the user; we would not claim that the AEZ design is simple. It has been getting simpler; we are now down to 63 lines of pseudocode.

Since McOE and COPA [2, 23], some recent AE schemes have been advertised as nonce-reuse misuse-resistant despite being online.⁸ But online schemes are never misuse-resistant in the sense originally defined [51].⁹ They never support automatic exploitation of novelty or verified redundancy [6] and are always vulnerable to a simple message-recovery attack [47]. We disagree with the presumption that two-pass AE schemes are routinely problematic; our work suggests that, on capable platforms, there isn’t even a performance penalty. Finally, short messages routinely dominate in networking applications, and we know of no application setting where it’s important to limit latency to just a few bytes, the implicit expectation for proposed online schemes.

This paper upends some well-entrenched assumptions. Before, AE-quality was always measured with respect to an aspirational goal; now we’re suggesting to employ an achievable one. Before, substantial ciphertext expansion was seen as a necessary property of any good AE scheme; now we’re saying to think of it as a user-supplied input and not be judgmental. Before, AE schemes and blockciphers were considered fundamentally different species of primitives; now we’re saying that, once the definitions are adequately strengthened, they’re pretty much the same thing. Before, one could either give a provable-security design or one that follows a more heuristic tradition; now we’re doing the one and yet still finding need for the other.

AEZ is one of 57 CAESAR submissions [8]. It’s distinguished by being the notionally strongest submission. We expect it to help clarify the costs and benefits of a well-designed two-pass scheme.

2 Prior AE Definitions

Fix an alphabet Σ . Typically Σ is $\{0, 1\}$ or $\{0, 1\}^8$, but other values, like $\Sigma = \{0, 1, \dots, 9\}$, are fine. For $x \in \Sigma^*$ let $|x|$ denote its length. We write ε for the empty string and $x \leftarrow X$ for uniformly sampling from a distribution X . If X is a finite set, it has the uniform distribution.

SYNTAX. We formalize a nonce-based AE scheme as a triple $\Pi = (\mathcal{K}, \mathcal{E}, \mathcal{D})$. The key space \mathcal{K} is a set of strings with an associated distribution. The encryption algorithm \mathcal{E} is deterministic and maps a four-tuple $(K, N, A, M) \in (\Sigma^*)^4$ to a value $C = \mathcal{E}_K^{N,A}(M)$ that is either a string in Σ^* or the distinguished symbol \perp . Later we will allow AD to be a vector of strings, $A \in (\Sigma^*)^*$. The distinction is insignificant insofar as we can always encode a vector of strings as a string. We require the existence of sets \mathcal{N} , \mathcal{A} and \mathcal{M} (the nonce space, AD space, and message space) such that $\mathcal{E}_K^{N,A}(M) \neq \perp$ iff $(K, N, A, M) \in \mathcal{K} \times \mathcal{N} \times \mathcal{A} \times \mathcal{M}$. The decryption algorithm \mathcal{D} is deterministic and takes a four-tuple (K, N, A, C) to a value $\mathcal{D}_K^{N,A}(C) \in \Sigma^* \cup \{\perp\}$. The length of a string-valued $C = \mathcal{E}_K^{N,A}(M)$ is not allowed to depend on anything beyond $|N|$, $|A|$ and $|M|$. In fact, usually $\lambda = |C| - |M|$ is a constant, in which case we call the scheme λ -*expanding* and refer to λ as the *ciphertext expansion*, or *stretch*. We require that if $C = \mathcal{E}_K^{N,A}(M)$ is a string then $\mathcal{D}_K^{N,A}(C) = M$. Algorithm \mathcal{D} *rejects* ciphertext C if $\mathcal{D}_K^{N,A}(C) = \perp$ and *accepts* it otherwise.

AE AND MRAE SECURITY. Both conventional-AE and MRAE security can be defined using a compact, all-in-one formulation [51]. Let $\Pi = (\mathcal{K}, \mathcal{E}, \mathcal{D})$ be an AE-scheme. Consider an adversary \mathcal{A}

⁸ By *online* we mean that the encryption algorithm can be realized in $O(1)$ memory and a single pass over M .

⁹ If the first bit of ciphertext doesn’t depend on the last bit of plaintext an adversary easily wins the MRAE game.

initialization Ideal_{Π} $K \leftarrow \mathcal{K}$ oracle $\text{Enc}(N, A, M)$ $C' \leftarrow \mathcal{E}_K(N, A, M)$ $C \leftarrow \Sigma^{ C' }$ return C oracle $\text{Dec}(N, A, C)$ return \perp	initialization Real_{Π} $K \leftarrow \mathcal{K}$ oracle $\text{Enc}(N, A, M)$ return $\mathcal{E}_K(N, A, M)$ oracle $\text{Dec}(N, A, C)$ return $\mathcal{D}_K(N, A, C)$	initialization PRI_{Π} for $(N, A) \in \mathcal{N} \times \mathcal{A} \times \mathcal{L}$ do $\pi_{N,A} \leftarrow \text{Inj}(\lambda)$ oracle $\text{Enc}(N, A, M)$ return $\pi_{N,A}(M)$ oracle $\text{Dec}(N, A, C)$ if $\exists M \in \mathcal{M}$ s.t. $\pi_{N,A}(M) = C$ then return M return \perp
	initialization REAL_{Π} $K \leftarrow \mathcal{K}$ oracle $\text{Enc}(N, A, \lambda, M)$ return $\mathcal{E}_K(N, A, \lambda, M)$ oracle $\text{Dec}(N, A, \lambda, C)$ return $\mathcal{D}_K(N, A, \lambda, C)$	initialization RAE_{Π} and RAE_{Π,S} for $(N, A, \lambda) \in \Sigma^* \times \Sigma^* \times \mathbb{N}$ do $\pi_{N,A,\lambda} \leftarrow \text{Inj}(\lambda)$ $\theta \leftarrow \varepsilon$ oracle $\text{Enc}(N, A, \lambda, M)$ return $\pi_{N,A,\lambda}(M)$ oracle $\text{Dec}(N, A, \lambda, C)$ if $\exists M \in \mathcal{M}$ s.t. $\pi_{N,A,\lambda}(M) = C$ then return M $M \leftarrow \perp$ \leftarrow for RAE_{Π} $(M, \theta) \leftarrow S(N, A, \lambda, C, \theta)$ \leftarrow for RAE_{Π,S} return M

Fig. 2. Old and new security notions. The top three games are the usual ones for defining AE and MRAE security (using **Real** and **Ideal**) and PRI security (using **Real** and **PRI**). The bottom two games are to define RAE security.

with access to an encryption oracle Enc and a decryption oracle Dec . We define the MRAE security of \mathcal{A} as $\text{Adv}_{\Pi}^{\text{mrae}}(\mathcal{A}) = \Pr[\mathcal{A}^{\text{Real}_{\Pi}} \Rightarrow 1] - \Pr[\mathcal{A}^{\text{Ideal}_{\Pi}} \Rightarrow 1]$, the difference in the probability that \mathcal{A} outputs 1 when run in the **Real** and **Ideal** games of Fig. 2. Both begin by selecting $K \leftarrow \mathcal{K}$. Game **Real** answers encryption queries (N, A, M) with $\mathcal{E}_K^{N,A}(M)$ and decryption queries (N, A, C) with $\mathcal{D}_K^{N,A}(C)$. Game **Ideal** answers $\text{Dec}(N, A, C)$ queries with \perp and $\text{Enc}(N, A, M)$ queries with $|C|$ uniformly chosen characters, where $C \leftarrow \mathcal{E}_K^{N,A}(M)$. For games **Real** and **Ideal**, adversaries may not repeat an Enc or Dec query, ask an Enc query $(N, A, M) \notin \mathcal{N} \times \mathcal{A} \times \mathcal{M}$, ask a Dec query $(N, A, C) \notin \mathcal{N} \times \mathcal{A} \times \Sigma^*$, or ask a Dec query (N, A, C) after an Enc query of (N, A, M) returned C .

The above definition captures MRAE security because repeated nonces were allowed and were properly serviced. For the conventional AE notion, $\text{Adv}_{\Pi}^{\text{ae}}(\mathcal{A})$, modify **Real** and **Ideal** by having an $\text{Enc}(N, A, M)$ query following an earlier $\text{Enc}(N, A', M')$ query return \perp . This has the same effect as prohibiting repeated N -values to the Enc oracle.

PRI SECURITY. We define security in the sense of a *pseudorandom-injection* (PRI) [51]. Fix a λ -expanding AE scheme $\Pi = (\mathcal{K}, \mathcal{E}, \mathcal{D})$; for now, λ is a constant associated to a (well-behaved) AE scheme. Let $\text{Adv}_{\Pi}^{\text{pri}}(\mathcal{A}) = \Pr[\mathcal{A}^{\text{Real}_{\Pi}} \Rightarrow 1] - \Pr[\mathcal{A}^{\text{PRI}_{\Pi}} \Rightarrow 1]$ with the oracles again defined in Fig. 2. There $\text{Inj}(\lambda)$ denotes the set of all one-to-one functions from Σ^* to Σ^* that increase the length of their inputs by λ -characters. The same query restrictions apply as before.

Besides defining PRI security, Rogaway and Shrimpton showed that, for large ciphertext expansion λ , the notion essentially coincides with MRAE security [51]. Below we clarify the role of the the ciphertext expansion by giving a sharper extended version of their result. To state our bound, define the *misuse count* as follows. Initially, set $r = 0$. Then, for each encryption query

$\text{Enc}(N, A, M)$, if there was a prior query (N, A, M') such that $|M'| = |M|$, increment r by 1. The final value of r is the misuse count. Below we show that good PRI security implies good MRAE security as long as q is small compared to $|\Sigma|^\lambda$ and r is small compared to $|\Sigma|^{(\lambda+m_{\min})/2}$ (with all variables defined below). The proof is in Appendix B.1.

Theorem 1. $|\mathbf{Adv}_\Pi^{\text{pri}}(\mathcal{A}) - \mathbf{Adv}_\Pi^{\text{mrae}}(\mathcal{A})| \leq 2q/|\Sigma|^\lambda + (r^2 + r)/|\Sigma|^{\lambda+m_{\min}+1}$ for any λ -expanding AE scheme Π and adversary \mathcal{A} , where r is the misuse count of \mathcal{A} 's queries, q is the number of queries it asks, and m_{\min} is the length of the shortest string in the message space.

In short, the PRI definition captures *best-possible* security of a λ -expanding AE scheme, while the MRAE formulation captures an unreachable ideal. The gap between the realizable and the ideal is formalized by Theorem 1. It is large if the ciphertext expansion is too small. This is so because any *actual* encryption algorithm must map distinct (N, A, M) and (N, A, M') to distinct ciphertexts, whence real encryption *can't* return uniformly random characters. Similarly, for any infinite message space, *some* unqueried ciphertexts *must* be valid, whence a decryption oracle that *always* returns an indication of invalidity is hoping for too much. Building on the PRI notion, we will now look towards an even more precise way to capture best-possible AE security.

3 RAE Security

SYNTAX. The principle difference between a PRI and an RAE scheme is that, for the latter, the ciphertext expansion λ is no longer a property of a scheme: it's as arbitrary *input* from the user. All values $\lambda \in \mathbb{N}$ should be allowed.¹⁰ Corresponding to this change, we'll write $\mathcal{E}_K^{N,A,\lambda}(M)$ and $\mathcal{D}_K^{N,A,\lambda}(C)$. The difference may look small, but its consequences are not.

Fix an alphabet Σ . Our formal definition again has an RAE scheme being a triple $\Pi = (\mathcal{K}, \mathcal{E}, \mathcal{D})$, but with the signature of \mathcal{E} and \mathcal{D} updated. Encryption algorithm \mathcal{E} is deterministic and maps a five-tuple $(K, N, A, \lambda, M) \in (\Sigma^*)^3 \times \mathbb{N} \times \Sigma^*$ to a string $C = \mathcal{E}_K^{N,A,\lambda}(M)$ of length $|M| + \lambda$. For maximal utility when realized, we are not permitting a return value of \perp : an RAE scheme must be able to encrypt any M using any N, A , and λ . Decryption algorithm \mathcal{D} is deterministic and takes a five-tuple (K, N, A, λ, C) to a value $\mathcal{D}_K^{N,A,\lambda}(C) \in \Sigma^* \cup \{\perp\}$. We require that $\mathcal{D}_K^{N,A,\lambda}(\mathcal{E}_K^{N,A,\lambda}(M)) = M$ for all K, N, A, λ, M . For now, we require if there's no M such that $C = \mathcal{E}_K^{N,A,\lambda}(M)$ then $\mathcal{D}_K^{N,A,\lambda}(C) = \perp$. Later in this section we will relax this requirement as a way to model the possibility of decryption algorithms that reveal information beyond an indication of invalidity.

RAE SECURITY. Let $\Pi = (\mathcal{K}, \mathcal{E}, \mathcal{D})$ be an RAE scheme over alphabet Σ . Its security is defined using the games **REAL** $_\Pi$ and **RAE** $_\Pi$ at the bottom of Fig. 2. (For the moment, ignore **RAE** $_{\Pi,S}$.) The adversary \mathcal{A} has two oracles, an encryption oracle **Enc** and a decryption oracle **Dec**. For game **REAL**, these are realized by the actual encryption and decryption algorithms, which now take in the argument λ . For game **RAE** $_\Pi$ we behave according to the family of random injections $\pi_{N,A,\lambda}$ chosen at the beginning of the game, responding to each encryption query (N, A, λ, M) with $C = \pi_{N,A,\lambda}(M)$ and responding to each decryption query (N, A, λ, C) by with $\pi_{N,A,\lambda}^{-1}(C)$, if that inverse exists, and \perp if it does not. We let $\mathbf{Adv}_\Pi^{\text{rae}}(\mathcal{A}) = \Pr[\mathcal{A}^{\text{REAL}_\Pi} \Rightarrow 1] - \Pr[\mathcal{A}^{\text{RAE}_\Pi} \Rightarrow 1]$. There are no restrictions on the kinds of queries the adversary may make.

¹⁰ It might be OK to set some reasonable upperbound $\lambda \leq \lambda_{\max}$, but there shouldn't be a nonzero lowerbound.

To gain some appreciation for the RAE definition, consider an adversary that asks to encrypt a message M using a single byte of stretch. Such a scheme would never be considered secure in the MRAE setting, since forgeries are trivially possible with probability $1/256$. But under the PRI viewpoint, that isn't a defect per se, as the user who requests one-byte expansion should *expect* that $1/256$ of all ciphertexts have *some* preimage. If a user should now try to decrypt the received ciphertext C using the same K, N, A but $\lambda = 0$, then plaintext *will* emerge, not an indication of invalidity, but a plaintext that is unrelated to the originally encrypted one.

DECRYPTION-CALL LEAKAGE. An AE scheme will fail to approximate the \mathbf{RAE}_Π abstraction if its decryption algorithm, when presented an invalid ciphertext, routinely returns anything beyond an indication of invalidity. We now explain how to relax this expectation so that it's OK to return additional material as long as it is known to be useless.

We said earlier that, for an RAE scheme $\Pi = (\mathcal{K}, \mathcal{E}, \mathcal{D})$ and any N, A, λ, C , if there's no M such that $C = \mathcal{E}_K^{N,A,\lambda}(M)$ then we expect $\mathcal{D}_K^{N,A,\lambda}(C)$ to return \perp . Let us now relax this requirement so that $\mathcal{D}_K^{N,A,\sigma}(C)$ may instead return a string, as long as its length is not $|C| - \lambda$. Any such string is trivially recognized as invalid, so, in effect, we are allowing \mathcal{D} to return both \perp and an arbitrary piece of side information Y . We are not suggesting that the “real” decryption algorithm should return anything other than \perp when presented an invalid ciphertext; instead, we are effectively overloading \mathcal{D} by folding into it a “leakage function” that captures that which a decryption algorithm's realization may leak about a presented ciphertext.

Using this generalized syntax, we define a game $\mathbf{RAE}_{\Pi,S}$ parameterized by a probabilistic algorithm S , the *simulator*. Again see Fig. 2. Simulator S is called upon to produce imitation ciphertexts when there's no preimage under $\pi_{N,A,\lambda}$. To accomplish this task S is provided nothing beyond the current oracle query and any saved state θ it wants to maintain. An RAE scheme is judged secure if there's a simulator S —preferably an efficient one—such that $(\mathcal{E}, \mathcal{D})$ is indistinguishable from the pair of oracles defined in $\mathbf{RAE}_{\Pi,S}$. We refine the RAE advantage by asserting that $\mathbf{Adv}_{\Pi,S}^{\text{rae}}(\mathcal{A}) = \Pr[\mathcal{A}^{\mathbf{REAL}_\Pi} \Rightarrow 1] - \Pr[\mathcal{A}^{\mathbf{RAE}_{\Pi,S}} \Rightarrow 1]$. The prior definition is just the former one where the simulator S ignores its input and returns (\perp, ε) .

The RAE definition effectively captures that, while it may be “nice” for decryption to reveal nothing but \perp on presentation of an invalid ciphertext, there are plenty of other things we could return without damaging privacy or authenticity. In fact, it really doesn't matter *what* is returned just so long as it's recognizably invalid and doesn't depend on the encryption function.

ILLUSTRATION. Fig. 3 illustrates two possibilities for how an RAE scheme might encrypt 2-bit strings with 2-bit ciphertext expansion ($\lambda = 2$). The key K , nonce N , and AD A are all fixed. For encryption, the four possible plaintexts are bijectively paired with four of the 16 possible ciphertexts. For decryption we show two possibilities. On the left is a *conventional* decryption algorithm: the 12 ciphertexts without a preimage decrypt to an indication of invalidity. One expects the simulator to always return (\perp, ε) . On the right is a *sloppy* decryption algorithm. The 12 ciphertexts with no preimage decrypt to 12 distinct strings, all recognizably invalid, all of the form $abcd \in \{0,1\}^4$ with $cd \neq 00$. Here the simulator S might sample without replacement from the named set of size 12.

DISCUSSION. The reader may have noticed that there is no distinction in the RAE security definition between the nonce N and associated data AD A . For this reason, either could be dropped—say the nonce—leaving us a signature $\mathcal{E}_K^{A,\lambda}(M)$ and $\mathcal{D}_K^{A,\lambda}(C)$. There's an especially good argument for doing this when the AD A is vector-valued: the user is already free to use one of its components

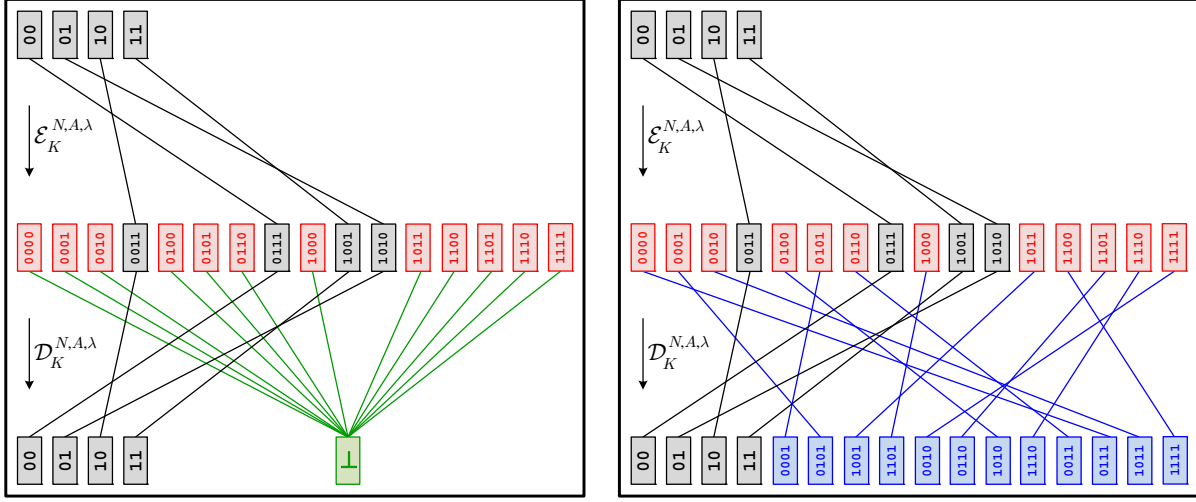


Fig. 3. Illustrating RAE. Two ways an RAE scheme might encrypt and decrypt a 2-bit string with 2-bit stretch.

as a nonce. Still, for greater uniformity in treatment across AE notions, and to encourage user’s to provide a nonce, we have retrained the both N and A .

We gave our definition of RAE into two stages only for pedagogical purposes: this paper offers only one definition for RAE. The the simulator S may be trivial or not; that is the only distinction.

Andreeva *et. al* [1] recently provided several security definitions also meant to capture the requirement that a decryption algorithm releases only harmless information when presented an invalid ciphertext and a repeated nonce. Our own work is radically different from theirs insofar as we provide a single definition, RAE, that rolls into it this, among many, considerations.

4 Verified Redundancy Enhances Authenticity

If a plaintext contains redundancy, one naively expects that verifying its presence upon decryption should enhance the authenticity guarantee provided. For the case of enciphering-based encryption, which provides no authenticity guarantee on its own, this has been formally supported [6, 51]. But even in this case the existing results are with respect to conventional notions of AE, and such notions are too blunt to capture what one expects from verified redundancy. This is because the notions “give up” as soon as a single ciphertext forgery is made.

Let $\Pi = (\mathcal{K}, \mathcal{E}, \mathcal{D})$ be RAE scheme and let $v: \Sigma^* \rightarrow \{0, 1\}$ be a function for indicating the “valid” strings: it determines $\mathcal{M}_v \subseteq \Sigma^*$ by $\mathcal{M}_v = \{M \in \Sigma^* : v(M) = 1\}$. Let $\Pi_v = (\mathcal{K}, \mathcal{E}, \tilde{\mathcal{D}})$ be the AE scheme built from Π that declares messages invalid if v says so: $\tilde{\mathcal{D}}_K^{N,A,\lambda}(C) = M$ if $|M| = |C| - \lambda$ and $v(M) = 1$, or if $|M| \neq |C| - \lambda$, where $M = \mathcal{D}_K^{N,A,\lambda}(C)$, while $\tilde{\mathcal{D}}_K^{N,A,\lambda}(C) = \mathbf{0} \parallel M$ otherwise, with $\mathbf{0}$ a canonical point in Σ . Let $d_v = \max_{\ell \in \mathbb{N}} \{(|\mathcal{M}_v \cap \Sigma^\ell|)/|\Sigma|^\ell\}$ be the *density* of \mathcal{M}_v .

Suppose, for example, that $\Sigma = \{0, 1\}$ and $d_v = 1/256$: there’s a byte worth of redundancy in the message space. We’d like to be able to make statements about the authenticity of Π_v such as “the chance that an adversary can forge 10 successive, distinct ciphertexts is negligibly more than 2^{-80} ”. Conventional AE definitions don’t let one say such a thing; they stop at the bound $q/|\Sigma|^\lambda$ where q is the number of queries and λ is the ciphertext expansion (assumed here to be a

constant). One would like to obtain a much sharper bound via d_v and λ —in our example, the forgery probability should be about $q(d_v/|\Sigma|^\lambda)^{10}$. This way, even if, say, $\lambda = 0$ and $d_v = 1/2$, we are *still* able to make strong statements about the security of Π_v . Intuitively, for an RAE scheme Π , the scheme Π_v should have about $(\lambda_{\min} + \log(1/d_v)) \log(|\Sigma|)$ bits of authenticity, where λ_{\min} is the minimum ciphertext expansion of any query—even after multiple successful forgeries and even in the presence of decryption leakage, future forgeries still remain just as hard.

To capture the intuition above, in Theorem 2 we show that Π_v itself is RAE-secure. The proof is in Appendix B.2. Consequently, in game **RAE**, for any query (N, A, λ, C) with $|C| = \ell + \lambda$ to Dec, the chance that this query is a successful forgery is about $|\mathcal{M}_v \cap \Sigma^\ell|/|\Sigma|^{\ell+\lambda} \leq d_v/|\Sigma|^\lambda$, despite any decryption leakage and past successful forgeries.

Theorem 2. Let Π and Π_v be defined as above. There is an explicitly given reduction \mathcal{R} with the following property. For any simulator S and any adversary \mathcal{A} , there is a simulator S' such that the adversary $\mathcal{B} = \mathcal{R}(\mathcal{A})$ satisfies $\mathbf{Adv}_{\Pi, S}^{\text{rae}}(\mathcal{B}) = \mathbf{Adv}_{\Pi_v, S'}^{\text{rae}}(\mathcal{A})$. Adversary \mathcal{B} makes the same queries as \mathcal{A} and has essentially the same running time.

Note that for good RAE security, we want the simulator S to be efficient. This is important for privacy, but when the concern is authenticity, it's less of an issue: a computationally-unbounded simulator may give the adversary some information that it can't compute itself, but as long as the adversary can't forge, whatever the adversary learns from the simulator is irrelevant for authenticity. Still, in the proof of Theorem 2, for each query (N, A, λ, C) , the simulator S' either runs S or samples from $\Sigma^\ell \cap \mathcal{M}_v$, where $\ell = |C| - \lambda$. For functions v that arises from real-world usage, sampling from $\Sigma^\ell \cap \mathcal{M}_v$ will be simple and efficient, whence S' will be about as fast as S itself.

5 Robust AE from a Generalized Blockcipher

We now show how to make an AE scheme that achieves RAE security. We begin with some basic definitions. Let $\mathcal{M} \subseteq \Sigma^*$ and \mathcal{T} be sets. A *blockcipher* $\tilde{\mathbb{E}}: \mathcal{K} \times \mathcal{T} \times \mathcal{M} \rightarrow \mathcal{M}$ is a mapping such that $\tilde{\mathbb{E}}_K^T(\cdot) = \mathbb{E}(K, T, \cdot)$ is a length-preserving permutation on \mathcal{M} for any K, T . Thus $|\tilde{\mathbb{E}}_K^T(X)| = |X|$ and there's a unique $\tilde{\mathbb{D}}: \mathcal{K} \times \mathcal{T} \times \{0, 1\}^* \rightarrow \mathcal{M} \cup \{\perp\}$ such that $\tilde{\mathbb{E}}_K^T(M) = C$ implies $\tilde{\mathbb{D}}_K^T(C) = M$ and $\tilde{\mathbb{D}}_K^T(C) = \perp$ when there's no M such that $\tilde{\mathbb{E}}_K^T(M) = C$. We call \mathcal{T} the *tweak space* of $\tilde{\mathbb{E}}$. When $|\mathcal{T}| = 1$ we make the tweak implicit, writing $\mathbb{E}: \mathcal{K} \times \mathcal{M} \rightarrow \mathcal{M}$, now with inverse \mathbb{D} . We define $\text{Perm}(\mathcal{M})$ as the set of all length-preserving permutations on \mathcal{M} , and $\text{Perm}(\mathcal{T}, \mathcal{M})$ the set of all mappings $\tilde{\pi}: \mathcal{T} \times \mathcal{M} \rightarrow \mathcal{M}$ where $\tilde{\pi}(T, \cdot) \in \text{Perm}(\mathcal{M})$ for all $T \in \mathcal{T}$. We usually use *encipher* instead of *encrypt* when speaking of applying a blockcipher, and similarly for *decipher* and *decrypt*.

An *arbitrary-input* blockcipher is a blockcipher with message space $\mathcal{M} = \Sigma^*$. To be maximally useful, we will want a rich tweak space as well. These are versatile and unconventional objects. Just a bit less general, a *wide-block* blockcipher has message space $\Sigma^{\geq n}$ for some fixed n . Again one prefers a rich tweak space.

The strong, tweakable, PRP advantage of an adversary \mathcal{A} attacking a blockcipher $\tilde{\mathbb{E}}$ is defined as $\mathbf{Adv}_{\tilde{\mathbb{E}}}^{\pm \text{prp}}(\mathcal{A}) = \Pr[K \leftarrow \mathcal{K} : \mathcal{A}^{\tilde{\mathbb{E}}_K(\cdot, \cdot), \tilde{\mathbb{D}}_K(\cdot, \cdot)} \Rightarrow 1] - \Pr[\tilde{\pi} \leftarrow \text{Perm}(\mathcal{T}, \mathcal{M}) : \mathcal{A}^{\tilde{\pi}(\cdot, \cdot), \tilde{\pi}^{-1}(\cdot, \cdot)} \Rightarrow 1]$. We'll write $\mathbf{Adv}_{\mathbb{E}}^{\pm \text{prp}}(\mathcal{A}) = \Pr[K \leftarrow \mathcal{K} : \mathcal{A}^{\mathbb{E}_K(\cdot), \mathbb{D}_K(\cdot)} \Rightarrow 1] - \Pr[\pi \leftarrow \text{Perm}(\mathcal{M}) : \mathcal{A}^{\pi(\cdot), \pi^{-1}(\cdot)} \Rightarrow 1]$ if there's no tweak. If we prohibit the adversary \mathcal{A} from querying the second oracle we drop the word “strong” and write $\mathbf{Adv}_{\tilde{\mathbb{E}}}^{\text{prp}}(\mathcal{A})$ and $\mathbf{Adv}_{\mathbb{E}}^{\text{prp}}(\mathcal{A})$ respectively.

ENCODE-THEN-ENCIPHER. Fix Σ . Let $\tilde{\mathbb{E}}: \mathcal{K} \times \mathcal{T} \times \Sigma^* \rightarrow \Sigma^*$ be an arbitrary-input blockcipher with tweak space $\mathcal{T} = \Sigma^* \times \Sigma^* \times \mathbb{N}$. Let $\tilde{\mathbb{D}}$ be its inverse. Let $\text{Encode}: \Sigma^* \times \mathbb{N} \rightarrow \Sigma^*$ be an injective function satisfying $|\text{Encode}(M, \lambda)| = |M| + \lambda$. We write the second argument to Encode as a subscript, $\text{Encode}_\lambda(M) \in \Sigma^{|M|+\lambda}$. An example encoding function is $\text{Encode}_\lambda(M) = M \parallel \mathbf{0}^\lambda$.

For any encoding function Encode there's a corresponding $\text{Decode}: \Sigma^* \times \mathbb{N} \rightarrow \Sigma^* \cup \{\perp\}$ such that $\text{Decode}_\lambda(X) = M$ if there's an M satisfying $\text{Encode}_\lambda(M) = X$, while $\text{Decode}_\lambda(X) = \perp$ if there's no such M . We expect Encode and Decode to be trivially computable, as in the example.

From $\tilde{\mathbb{E}}: \mathcal{K} \times \mathcal{T} \times \Sigma^* \rightarrow \Sigma^*$ and Encode we define the encode-then-encipher construction as the RAE scheme $\text{EtE}[\text{Encode}, \tilde{\mathbb{E}}] = (\mathcal{K}, \mathcal{E}, \mathcal{D})$ where

- $\mathcal{E}_K^{N,A,\lambda}(M) = \tilde{\mathbb{E}}_K^{(N,A,\lambda)}(\text{Encode}_\lambda(M))$,
- $\mathcal{D}_K^{N,A,\lambda}(C) = M$ if $\tilde{\mathbb{D}}_K^{(N,A,\lambda)}(C) = X$ and M satisfies $\text{Encode}_\lambda(M) = X$,
- $\mathcal{D}_K^{N,A,\lambda}(C) = X$ if $\tilde{\mathbb{D}}_K^{(N,A,\lambda)}(C) = X$ and there's no M satisfying $\text{Encode}_\lambda(M) = X$.

We stress that decryption does not simply return \perp when is called on an invalid (N, A, λ, C) , as is conventionally done; instead, we define decryption to “leak” the entire improperly encoded string X . Nonetheless, Theorem 3 shows that $\text{EtE}[\text{Encode}, \tilde{\mathbb{E}}]$ is RAE-secure when $\tilde{\mathbb{E}}$ is secure as a strong, tweakable PRP. Its proof appears in Appendix B.3.

Theorem 3 (EtE is RAE-secure). Let Encode and $\tilde{\mathbb{E}}: \mathcal{K} \times \mathcal{T} \times \Sigma^* \rightarrow \Sigma^*$ be defined as above. Then there's an explicitly given reduction \mathcal{R} and an efficient simulator S with the following property. For any adversary \mathcal{A} , the adversary $\mathcal{B} = \mathcal{R}(\mathcal{A})$ satisfies $\mathbf{Adv}_{\text{EtE}[\text{Encode}, \tilde{\mathbb{E}}], S}^{\text{rae}}(\mathcal{A}) \leq \mathbf{Adv}_{\tilde{\mathbb{E}}}^{\pm \text{prp}}(\mathcal{B})$. It makes at most q queries whose total length is at most that of \mathcal{A} 's queries plus $q\lambda_{\max}$, where q is the number of \mathcal{A} 's queries and λ_{\max} is the largest stretch among them. The running time of \mathcal{B} is about that of \mathcal{A} , plus the time associated to computations of Encode and Decode .

6 Wide-Block Enciphering: AEZ-core

Let $n \geq 1$ be an integer and let $\{0, 1\}^{\geq 2n} = \{x \in \{0, 1\}^*: |x| \geq 2n\}$. Define the *block length* of a string x as $\lceil |x|/n \rceil$. We show how to build a strong PRP on $\{0, 1\}^{\geq 2n}$ from a TBC on $\{0, 1\}^n$. We'll use about 2.5 TBC calls per n -bit block. Later we'll instantiate the TBC using mostly AES4, employing the accelerated provable-security paradigm to selectively scale-down. This will reduce the amortized cost to about one AES call per block. Also see Appendix C for how to tweak a wide-block blockcipher.

We begin by recalling the definition of a pseudorandom function (PRF) $f: \mathcal{K} \times \mathcal{M} \rightarrow \{0, 1\}^n$. For an adversary \mathcal{A} attacking f , its PRF advantage is $\mathbf{Adv}_f^{\text{prf}}(\mathcal{A}) = \Pr[K \leftarrow \mathcal{K}: \mathcal{A}^{f_K(\cdot)} \Rightarrow 1] - \Pr[\rho \leftarrow \text{Func}(\mathcal{M}, n): \mathcal{A}^{\rho(\cdot)} \Rightarrow 1]$ where $\text{Func}(\mathcal{M}, n)$ is the set of all functions from \mathcal{M} to $\{0, 1\}^n$.

AEZ-CORE. We'll assume a tweak space $\mathcal{T} = \{\mathbf{a}, \mathbf{u}, \mathbf{uu}, \mathbf{v}, \mathbf{vv}, \mathbf{x}, \mathbf{xx}, \mathbf{y}, \mathbf{yy}\} \cup (\{\mathbf{a}, \mathbf{aa}\} \times \mathbb{N})$. Suppose we have a PRF $f: \mathcal{K} \times (\mathcal{T} \times \{0, 1\}^n) \rightarrow \{0, 1\}^n$. One can instantiate this with a TBC \tilde{E} on $\{0, 1\}^n$ by setting $f_K(K, (T, X)) = \tilde{E}_K^T(X)$. Consider the wide-block blockcipher $\text{AEZ-core}[f]$ defined and illustrated in Fig. 4. It loosely follows EME/EME2 [25, 27, 30], but avoids all doubling operations and only uses the forward direction of the underlying TBC. $\text{AEZ-core}[f]$ operates on $\mathcal{M} = \{0, 1\}^{\geq 2n}$ and itself takes in no tweak. Theorem 4 shows that it's a strong PRP. The proof is in Appendix B.4.

Theorem 4. Let $n \geq 1$ be an integer and let \mathcal{T} and f be as above. There's an explicitly given reduction \mathcal{R} with the following property. For any adversary \mathcal{A} , adversary $\mathcal{B} = \mathcal{R}(\mathcal{A})$ satisfies

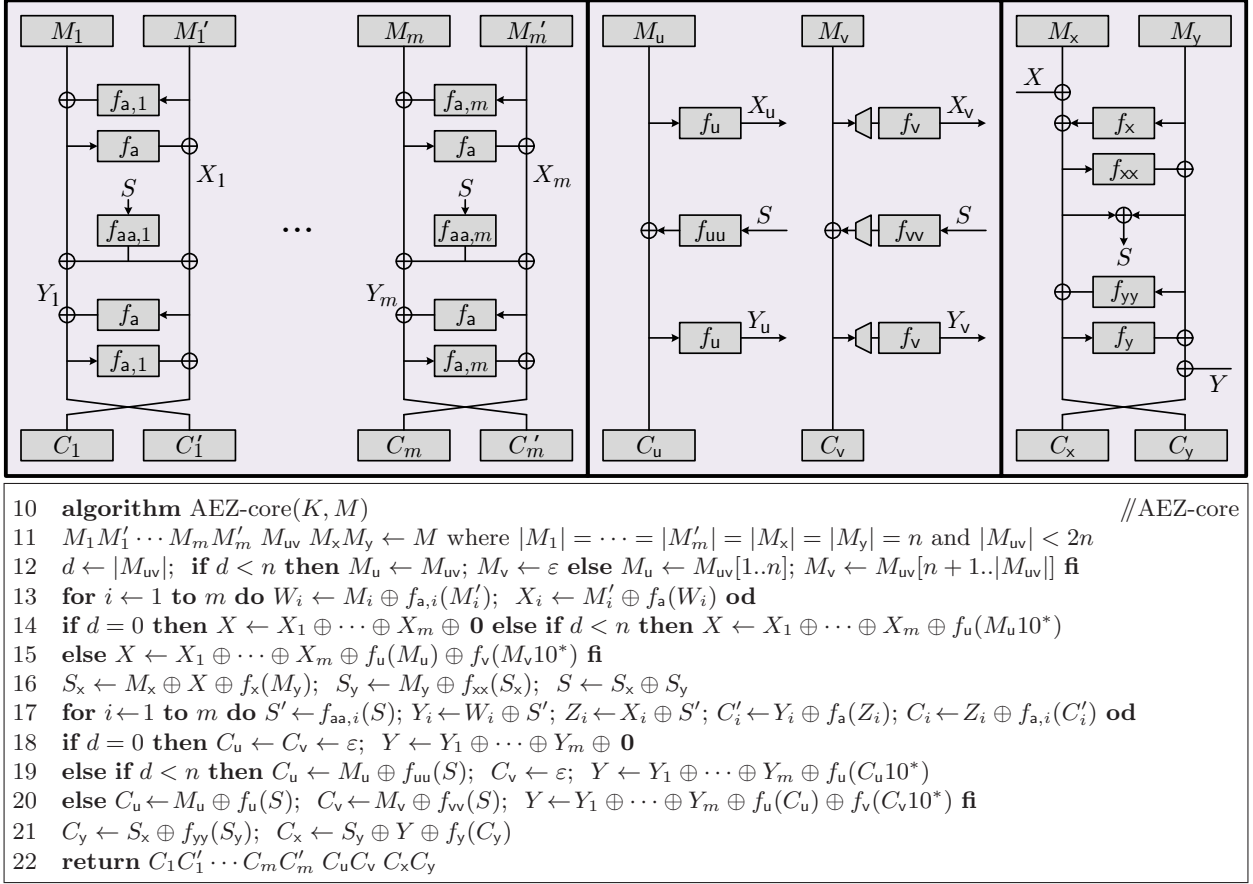


Fig. 4. The AEZ-core $[f]$ construction. The method builds a strong-PRP on $\{0, 1\}^{\geq 2n}$ from an n -bit-output PRF f that operates on its subscript and argument. It's key K is implicit. The PRF can be realized by a TBC.

$\text{Adv}_{\text{AEZ-core}[f]}^{\pm \text{prp}}(\mathcal{A}) \leq \text{Adv}_f^{\text{prf}}(\mathcal{B}) + 2\sigma^2/2^n$ where σ is the total block length of \mathcal{A} 's queries. Adversary \mathcal{B} uses the same running time as \mathcal{A} , and makes at most 2.5σ queries.

DISCUSSION. AEZ-core and its inverse are almost the same: the only change needed is to take the rightmost column of tweaks in reverse order. Given that one must have *some* asymmetry in an RAE scheme—an involution is certainly RAE-insecure—this is about as symmetric a design as one could hope for. A high degree of symmetry can help maximize efficiency of both hardware and software. Symmetry is the reason for the wire-crossing just before each $C_i C'_i$.

Among the efficiency characteristics of AEZ-core is that one can selectively decrypt a chosen block about 2.5 times more quickly than decrypting everything. When AEZ-core is turned into an RAE scheme by the EtE construction, this observation is put to good use in achieving fast rejection of ciphertexts whose final 0^τ bits is plaintext is not correct. That it is undamaging to release this timing information is guaranteed by results already show—in particular, that it is ok to release the *entire* speculative plaintext.

AEZ-core confines “specialized” processing to the final 2–4 blocks. This helps with efficiency and simplicity compared to having specialized processing at the beginning or at the beginning and end. In particular, the 0^τ authenticator used to make an RAE scheme will be put at the *end* of the

message (adding a variable number of zero-bits at beginning could destroy word alignment) and, as long as $\tau \leq 2n$, it will be found in the final two blocks.

Numerous alternatives to AEZ-core were considered before arriving at our design. Correct alternatives we know are slower or more complex, while most simplifications are wrong. For example, consider trying to cheapen the design by using $c_i \cdot f_{aa,1}(S)$ instead of $f_{aa,i}(S)$ where each c_i is a public constant and the product is in $\text{GF}(2^n)$. This fails for *any* choice of c_i . See Appendix D.

One variant of AEZ-core that *does* work is to eliminate the “left-hand” xor coming out of $f_{aa,i}$. (One then has to define X_i as the output of f_a instead of that output xor’ed with M'_1 , and change Y_i similarly.) We have kept this xor because it’s needed for symmetry.

7 Definition of AEZ

So far we have described two key elements of AEZ: the EtE construction and the AEZ-core[f] wide-block blockcipher. Now we give AEZ’s complete description. First a bit of notation.

NOTATION. The bit length of a string X is written $|X|$. For the bitwise xor of unequal-length strings, drop the necessary number of rightmost bits from the longer ($10 \oplus 0100 = 11$). For X a string, let $X0^* = X0^p$ with p the smallest number such that 128 divides $|X| + p$. By \mathcal{X}^* we denote the set of all strings over the alphabet \mathcal{X} , including ε . By $(\mathcal{X}^*)^*$ we denote the set of all vectors over \mathcal{X}^* , including the empty vector.

If $|X| = n$ and $1 \leq i \leq j \leq n$ then $X(i)$ is the i th bit of X (indexing from the left starting at 1), $\text{msb}(X) = X(1)$, and $X(i..j) = X(i) \cdots X(j)$. Let $[n]_t$ be the t -bit string representing $n \bmod 2^t$ and let $[n]$ be shorthand for $[n]_8$; for example $[0]^{16} = ([0]_8)^{16} = 0^{128}$ and $[1]^{16} = (00000001)^{16}$. A block is 128 bits. Let $\mathbf{0} = 0^{128}$. If $X = a_1 \cdots a_{128}$ is a block ($a_i \in \{0, 1\}$) then we define $X \ll 1 = a_2 \cdots a_{128} 0$. For $n \in \mathbb{N}$ and $X \in \{0, 1\}^{128}$ define $n \cdot X$ by asserting that $0 \cdot X = \mathbf{0}$ and $1 \cdot X = X$ and $2 \cdot X = (X \ll 1) \oplus [135 \cdot \text{msb}(X)]_{128}$ and $2n \cdot X = 2 \cdot (n \cdot X)$ and $(2n + 1) \cdot X = (2n \cdot X) \oplus X$.

For $K, X \in \{0, 1\}^{128}$ we write $\text{aesenc}(X, K)$ for a single round of AES: **SubBytes**, **ShiftRows**, **MixColumns**, then an **AddRoundKey** with K . For $\mathbf{K} = (K_0, K_1, K_2, K_3, K_4)$ a list of five blocks let $\text{AES4}_{\mathbf{K}}(X) = \text{AES4}(\mathbf{K}, X)$ be $\text{aesenc}(\text{aesenc}(\text{aesenc}(\text{aesenc}(X \oplus K_0, K_1), K_2), K_3), K_4)$. For $\mathbf{K} = (K_0, K_1, \dots, K_{10})$ a list of 11 blocks define $\text{AES10}_{\mathbf{K}}(X) = \text{AES10}(\mathbf{K}, X)$ like we defined **AES4** but with ten rounds of **aesenc**. We do not omit the final-round **MixColumns**.

AEZ DEFINITION. See Figs. 5 and 6 for the definition of AEZ, and Fig. 7 for an illustration. Most of it is self-explanatory. We briefly mention some of the algorithm’s more unusual elements.

AEZ operates on arbitrary byte strings. Not only is the plaintext $M \in \text{BYTE}^*$ arbitrary, but also the key $K \in \text{BYTE}^*$ and nonce $N \in \text{BYTE}^*$. The AD is even more general: an arbitrary-length vector of arbitrary byte strings, $A \in (\text{BYTE}^*)^*$. The requested ciphertext expansion of $\lambda \in \mathbb{N}$ bytes will usually be measured in $\tau = 8\lambda$ bits.

At line 215, Encipher-AEZ-tiny may xor a bit into the ciphertext just before the algorithm’s conclusion. This is done to avoid a simple random-permutation distinguishing attacks, for very short strings, based on the fact that Feistel networks only generate *even* permutations [32]. A similar trick, conditionally swapping two fixed points, has been used before [46]. Our approach has the benefit that the natural implementation is constant-time.

We define $\text{Decipher}(K, T, Y)$ as the unique X such that $\text{Encipher}(K, T, X) = Y$. Logically, this is all we need say for the specification to be well-defined. Still, the additional pseudocode is easy

100	algorithm ENCRYPT(K, N, A, τ, M)	//AEZ authenticated encryption
101	$X \leftarrow M \parallel 0^\tau$; $(A_1, \dots, A_m) \leftarrow A$	
102	$T \leftarrow ([\tau]_{128}, N, A_1, \dots, A_m)$	
103	if $M = \varepsilon$ then return AEZ-prf(K, T, τ)	
104	return Encipher(K, T, X)	
110	algorithm DECRYPT(Key, N, A, τ, C)	//AEZ authenticated decryption
111	$(A_1, \dots, A_m) \leftarrow A$; $T \leftarrow ([\tau]_{128}, N, A_1, \dots, A_m)$	
112	if $ C < \tau$ then return \perp	
113	if $ C = \tau$ then if $C = \text{AEZ-prf}(K, T, \tau)$ then return ε else return \perp fi	
114	$X \leftarrow \text{Decipher}(K, T, C)$	
115	$M \parallel Z \leftarrow X$ where $ Z = \tau$	
116	if $(Z = 0^\tau)$ then return M else return \perp	
200	algorithm Encipher(K, T, X)	//AEZ enciphering
201	if $ X < 256$ then return Encipher-AEZ-tiny(K, T, X)	
202	if $ X \geq 256$ then return Encipher-AEZ-core(K, T, X)	
210	algorithm Encipher-AEZ-tiny(K, T, M)	//AEZ-tiny enciphering
211	$m \leftarrow M $; $n \leftarrow m/2$; $\Delta \leftarrow \text{AEZ-hash}(K, T)$	
212	if $m = 8$ then $k \leftarrow 24$ else if $m = 16$ then $k \leftarrow 16$ else if $m < 128$ then $k \leftarrow 10$ else $k \leftarrow 8$ fi	
213	$L \leftarrow M(1 \dots n)$; $R \leftarrow M(n+1 \dots m)$; if $m \geq 128$ then $j \leftarrow 6$ else $j \leftarrow 7$ fi	
214	for $i \leftarrow 0$ to $k-1$ do $R' \leftarrow L \oplus ((E_K^{0,j}(\Delta \oplus R10^* \oplus [i]_{128}))(1 \dots n))$; $L \leftarrow R$; $R \leftarrow R'$ od	
215	$C \leftarrow R \parallel L$; if $m < 128$ then $C \leftarrow C \oplus (E_K^{0,3}(\Delta \oplus (C0^* \vee 10^*)) \wedge 10^*)$ fi	
216	return C	
220	algorithm Encipher-AEZ-core(K, T, M)	//AEZ-core enciphering
221	$\Delta \leftarrow \text{AEZ-hash}(K, T)$	
222	$M_1 M'_1 \dots M_m M'_m M_{uv} M_x M_y \leftarrow M$ where $ M_1 = \dots = M'_m = M_x = M_y = 128$ and $ M_{uv} < 256$	
223	$d \leftarrow M_{uv} $; if $d \leq 127$ then $M_u \leftarrow M_{uv}$; $M_v \leftarrow \varepsilon$ else $M_u \leftarrow M_{uv}[1..128]$; $M_v \leftarrow M_{uv}[129.. M_{uv}]$ fi	
224	for $i \leftarrow 1$ to m do $W_i \leftarrow M_i \oplus E_K^{1,i}(M'_i)$; $X_i \leftarrow M'_i \oplus E_K^{0,0}(W_i)$ od	
225	if $d = 0$ then $X \leftarrow X_1 \oplus \dots \oplus X_m \oplus \mathbf{0}$ else if $d \leq 127$ then $X \leftarrow X_1 \oplus \dots \oplus X_m \oplus E_K^{0,4}(M_u 10^*)$	
226	else $X \leftarrow X_1 \oplus \dots \oplus X_m \oplus E_K^{0,4}(M_u) \oplus E_K^{0,5}(M_v 10^*)$ fi	
227	$S_x \leftarrow M_x \oplus \Delta \oplus X \oplus E_K^{0,1}(M_y)$; $S_y \leftarrow M_y \oplus E_K^{-1,1}(S_x)$; $S \leftarrow S_x \oplus S_y$	
228	for $i \leftarrow 1$ to m do $S' \leftarrow E_K^{2,i}(S)$; $Y_i \leftarrow W_i \oplus S'$; $Z_i \leftarrow X_i \oplus S'$; $C'_i \leftarrow Y_i \oplus E_K^{0,0}(Z_i)$; $C_i \leftarrow Z_i \oplus E_K^{1,i}(C'_i)$ od	
229	if $d = 0$ then $C_u \leftarrow C_v \leftarrow \varepsilon$; $Y \leftarrow Y_1 \oplus \dots \oplus Y_m \oplus \mathbf{0}$	
230	else if $d \leq 127$ then $C_u \leftarrow M_u \oplus E_K^{-1,4}(S)$; $C_v \leftarrow \varepsilon$; $Y \leftarrow Y_1 \oplus \dots \oplus Y_m \oplus E_K^{0,4}(C_u 10^*)$	
231	else $C_u \leftarrow M_u \oplus E_K^{-1,4}(S)$; $C_v \leftarrow M_v \oplus E_K^{-1,5}(S)$; $Y \leftarrow Y_1 \oplus \dots \oplus Y_m \oplus E_K^{0,4}(C_u) \oplus E_K^{0,5}(C_v 10^*)$ fi	
232	$C_y \leftarrow S_x \oplus E_K^{-1,2}(S_y)$; $C_x \leftarrow S_y \oplus \Delta \oplus Y \oplus E_K^{0,2}(C_y)$	
233	return $C_1 C'_1 \dots C_m C'_m C_u C_v C_x C_y$	

Fig. 5. Main routines of AEZ. The tweakable blockcipher E , the hash AEZ-hash , and the PRF AEZ-prf are all defined in Fig. 6. Requested ciphertext expansion is $\tau = 8 \cdot \lambda$ bits.

to describe. AEZ-tiny deciphering is identical to AEZ-tiny enciphering except we must count backwards instead of forwards, and must do the even-cycles correction (line 215) at the beginning instead of the end. Specifically, $\text{Decipher-AEZ-tiny}(K, T, M)$ is identical to $\text{Encipher-AEZ-tiny}(K, T, M)$ except that line 214 is changed to count from $k-1$ down to 0, while line 215 has each C replaced by M before moving the line up to just after line 212. And AEZ-core deciphering is identical to AEZ-core enciphering except that we must take the xy -tweaks in reverse order. Specifically, $\text{Decipher-AEZ-core}(K, T, M)$ is identical to $\text{Encipher-AEZ-core}(K, T, M)$ except we swap tweaks $(0, 1)$ and $(0, 2)$, and we swap tweaks $(-1, 1)$ and $(-1, 2)$. These appear at lines 227 and 232.

The TBC $E_K^{i,j}(X)$ takes a tweak $(i, j) \in \{-1, 0\} \times [0..7] \cup \{1, 2, 3\} \times \mathbb{N}$. The first component selects between AES10 (when $i = -1$) and AES4 (when $i \geq 0$). Either way, the construction is based on

300	algorithm AEZ-hash(K, T)	//AXU hash. T is a vector of strings
301	$(T_1, \dots, T_t) \leftarrow T$	
302	for $i \leftarrow 1$ to t do	
303	$m \leftarrow \max(1, \lceil T_i /128 \rceil)$; $X_1 \dots X_m \leftarrow T_i$ where $ X_1 = \dots = X_{m-1} = 128$	
305	if $ X_m = 128$ then $\Delta_i \leftarrow E_K^{2+i,1}(X_1) \oplus \dots \oplus E_K^{2+i,m}(X_m)$	
306	if $ X_m < 128$ then $\Delta_i \leftarrow E_K^{2+i,1}(X_1) \oplus \dots \oplus E_K^{2+i,m-1}(X_{m-1}) \oplus E_K^{2+i,0}(X_m 10^*)$	
307	return $\Delta_1 \oplus \dots \oplus \Delta_t \oplus \mathbf{0}$	
310	algorithm AEZ-prf(K, T, τ)	//PRF used when $M = \varepsilon$
311	$\Delta \leftarrow \text{AEZ-hash}(K, T)$	
312	return $(E_K^{-1,3}(\Delta) \parallel E_K^{-1,3}(\Delta \oplus [1]_{128}) \parallel E_K^{-1,3}(\Delta \oplus [2]_{128}) \parallel \dots)[1..\tau]$	
400	algorithm $E_K^{i,j}(X)$	//Scaled-down TBC
401	$(I, J, L) \leftarrow \text{Extract}(K)$	
402	$k_0 \leftarrow (\mathbf{0}, I, J, L, \mathbf{0})$; $k_1 \leftarrow (\mathbf{0}, J, L, I, \mathbf{0})$; $k_2 \leftarrow (\mathbf{0}, L, I, J, I)$	
403	$K \leftarrow (\mathbf{0}, I, L, J, I, L, J, I, L, J, I)$	
404	if $i = -1$ and $0 \leq j \leq 7$ then return $\text{AES10}_K(X \oplus jJ)$	
405	if $i = 0$ and $0 \leq j \leq 7$ then return $\text{AES4}_{k_0}(X \oplus jJ)$	
406	if $1 \leq i \leq 2$ and $j \geq 1$ then return $\text{AES4}_{k_i}(X \oplus (j \bmod 8)J \oplus 2^{\lfloor (j-1)/8 \rfloor} L)$	
407	if $i \geq 3$ and $j \geq 1$ then return $\text{AES4}_{k_0}(X \oplus (j \bmod 8)J \oplus 2^{\lfloor (j-1)/8 \rfloor} \cdot L \oplus (i-2)8J)$	
408	if $i \geq 3$ and $j = 0$ then return $\text{AES4}_{k_0}(X \oplus (i-2)8J)$	
410	algorithm Extract(K)	//Map key to subkeys
411	$z \leftarrow [0][1] \dots [15]$; $m \leftarrow \max(1, \lceil K /128 \rceil)$; $K_1 \dots K_m \leftarrow K$ where $ K_1 = \dots = K_{m-1} = 128$	
412	for $i \leftarrow 1$ to 3 do	
413	for $j \leftarrow 0$ to m do $c_{i,j} \leftarrow \text{AES4}_{(z,z,z,z,z,z)}([i]_{64}[j]_{64})$; $C_{i,j} \leftarrow (c_{i,j}, c_{i,j}, c_{i,j}, c_{i,j}, c_{i,j})$; od	
414	if $ K_m = 128$ then $X_i \leftarrow \text{AES4}_{C_{i,1}}(K_1) \oplus \text{AES4}_{C_{i,2}}(K_2) \oplus \dots \oplus \text{AES4}_{C_{i,m-1}}(K_{m-1}) \oplus \text{AES4}_{C_{i,m}}(K_m)$	
415	if $ K_m < 128$ then $X_i \leftarrow \text{AES4}_{C_{i,1}}(K_1) \oplus \text{AES4}_{C_{i,2}}(K_2) \oplus \dots \oplus \text{AES4}_{C_{i,m-1}}(K_{m-1}) \oplus \text{AES4}_{C_{i,0}}(K_m 10^*)$	
416	return (X_1, X_2, X_3)	

Fig. 6. AEZ’s hash, PRF, and TBC. The last carries out key processing that an implementation would normally do at session-setup.

XE [35, 49]. Still, algorithm E is not secure as a tweakable-PRP: this is where the scaling-down has been done.

Note the mod 8’s at lines 406–407. Unlike the offset sequence used for OCB [34], we limit ourselves to eight successive J values; after that, we add in the next power-of-two times L . This allows a small table of $2^j \cdot J$ values to be precomputed and used regardless of the length of the message. In this way we limit the frequency of doublings yet avoid number-of-trailing-zeros calculation.

To deal with arbitrary-length keys, procedure Extract turns the provided key into 48 bytes, (I, J, L) , using an almost-universal hash function with a fixed but “random-looking” key. The approach is rooted in the leftover hash lemma [3, 17, 29]. The hash we use is simple and parallelizable, and in the spirit of AEZ-hash.

We impose a limit that AEZ be used for at most 2^{48} bytes of data (about 280 TB); by that time, the user should rekey. This usage limit stems from the existence of birthday attacks on AEZ, as well as the use of AES4 to create a universal hash function.

COST ACCOUNTING. Let us summarize the computational cost of AEZ in “AES-equivalents,” where 1 AES-equivalents is 10 AES rounds. Assume a message of m blocks, the last of which may be fragmentary. To encipher or decipher $m \geq 2$ blocks: at most $m + 2.4$ AES-equivalents (latency 3.6). This assumes K , N , τ , and A have already been processed. To encrypt or decrypt $m \geq 2$ blocks: at most $m + 3.8$ AES-equivalents (latency 3.6). This assumes that K , A , and τ

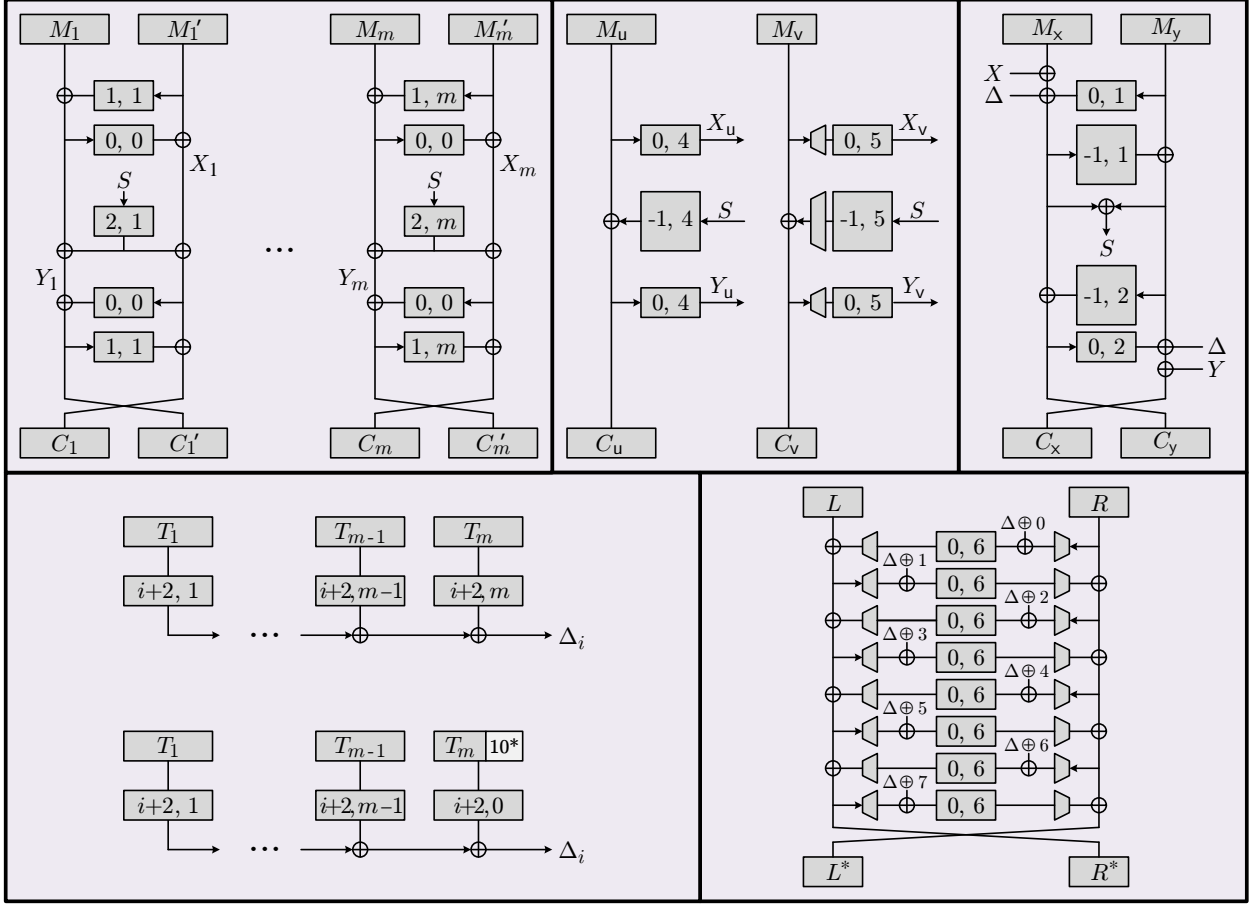


Fig. 7. Illustrating AEZ enciphering. Rectangles with pairs of numbers are TBCs, the pair being the tweak (the key, always K , is not shown). **Top row:** enciphering a message M of (32 or more bytes) with AEZ-core. The diagram shows processing a string that is (exclude the middle panel) or isn't (include the middle panel) a multiple of 16 bytes. **Bottom left:** AEZ-hash is an xor-universal hash built from AES4. It computes $\Delta = \bigoplus \Delta_i$ from a vector-valued tweak T comprising A , N , and τ . Its i -th component $T_1 \cdots T_m$ is hashed as shown. **Bottom right:** AEZ-tiny, when operating on a string $M = L \parallel R$ of 16–31 bytes. More rounds are used if M has 1–15 bytes.

have already been processed and that $|N| \leq 128$ and $\tau = 128$. To reject an invalid ciphertext of $m \geq 2$ blocks: at most $0.4m + 2.4$ AES-equivalents (latency 2.8). Same assumptions. To setup an m block key: $1.2m$ AES-equivalents (latency 0.4). This assumes that needed constants have been precomputed. To setup a string-values AD: $0.4m$ (latency 0.4). To encipher or decipher messages of 1–15 bytes is somewhat slower: 10, 6.8, and 4.4 AES-equivalents for 1, 2, and 3 bytes.

PARAMETERIZED COUNTERPARTS. For a TBC-parameterized generalization of AEZ, let $\text{AEZ}[\tilde{E}]$ be identical to AEZ except for using the TBC $\tilde{E}: \mathcal{K} \times \mathcal{T}_{\text{aez}} \times \{0, 1\}^{128} \rightarrow \{0, 1\}^{128}$ in place of E (assume the correct tweak-space \mathcal{T}_{aez}). The key space of \tilde{E} is then taken as the key space for the constructed RAE scheme. Note that $\text{AEZ} = \text{AEZ}[E]$, with E the algorithm defined by lines 400–416.

Taking the above a step further, given a conventional blockcipher $E: \mathcal{K} \times \{0, 1\}^{128} \rightarrow \{0, 1\}^{128}$ we can define $\text{AEZ}[E]$ as $\text{AEZ}[\tilde{E}]$ where $\tilde{E}_K^{i,j}(X) = E_K(X \oplus (i+1)I \oplus jJ)$ for $I = E_K(\mathbf{0})$ and $J = E_K(\mathbf{1})$. The scheme $\text{AEZ}[\text{AES}]$ can be regarded as a natural “scaled up” version of AEZ. We emphasize that AEZ is *not* $\text{AEZ}[\text{AES}]$, which is about 2.5 times as slow.

Schemes $\text{AEZ}[\tilde{E}]$ and $\text{AEZ}[E]$ are close to AEZ , but enjoy conventional provable-security guarantees, as we now describe.

8 Security of $\text{AEZ}[\tilde{E}]$ and $\text{AEZ}[E]$

We show that if \tilde{E} is secure as a tweakable PRP then $\text{AEZ}[\tilde{E}]$ is RAE-secure. In fact, the statement holds even if the decryption algorithm is modified so as to leak the entire improperly encoded string obtained by deciphering an invalid ciphertext. So, for the remainder of this section, assume the modification of AEZ in which the **else** clause of line 116 returns the deciphered message X rather than \perp . This change only makes our results stronger, explicitly modeling the *possibility* of a decryption implementation leaking some or all of X . The *actual* decryption algorithm returns \perp .

Our provable-security results for AEZ need to assume that the adversary avoids enciphering or deciphering extremely short strings—at least those under 16 bytes, say, for which AEZ -tiny, a Feistel-based construction, will not enjoy a desirable bound. While provably-secure options are now available for enciphering very short strings, they still do not have competitive efficiency.

As the alphabet for AEZ is $\Sigma = \text{BYTE}$, in this section we write $|x|$ for the byte length of x . For an encryption query (N, A, λ, M) , define the number of blocks processed as $\lceil |N|/16 \rceil + \sum_i \lceil |A_i|/16 \rceil + \lceil (|M| + \lambda)/16 \rceil$. This query is *small* if $M \neq \varepsilon$ and $16 \leq |M| + \lambda < 32$, and *tiny* if $M \neq \varepsilon$ and $|M| + \lambda < 16$. Likewise, for a decryption query (N, A, λ, C) , the number of blocks processed is $\lceil |N|/16 \rceil + \sum_i \lceil |A_i| \rceil + \lceil (|C|)/16 \rceil$. The query is *small* if $16 \leq |C| < 32$ and $|C| \neq \lambda$, and *tiny* if $|C| \neq \lambda$ and $|C| < 16$. The proof for the following is in Appendix B.5.

Theorem 5. Let $\tilde{E}: \mathcal{K} \times \mathcal{T}_{\text{aez}} \times \{0, 1\}^{128} \rightarrow \{0, 1\}^{128}$ be a TBC and $\Pi = \text{AEZ}[\tilde{E}]$. Then there are efficient, explicitly given algorithms \mathcal{R} and \mathcal{S} with the following property. Let \mathcal{A} be an adversary for attacking Π . Assume it never asks any small or tiny query. Then $\mathcal{B} = \mathcal{R}(\mathcal{A})$ satisfies $\mathbf{Adv}_{\Pi, \mathcal{S}}^{\text{rae}}(\mathcal{A}) \leq 3.5s^2/2^{128} + \mathbf{Adv}_{\tilde{E}}^{\text{prp}}(\mathcal{B})$, where s is the total number of processed blocks, plus 2 blocks per message. Adversary \mathcal{B} makes at most $2.5s$ queries and has about the same running time as \mathcal{A} .

An alternative approach to justifying the security of AEZ is to speak of the security of $\text{AEZ}[E]$, the cousin of AEZ defined from a conventional blockcipher E using the XE construction to make the needed TBC. Its security can be captured by the following result. The proof is in Appendix B.6.

Theorem 6. Let $E: \mathcal{K} \times \{0, 1\}^{128} \rightarrow \{0, 1\}^{128}$ be a blockcipher and $\Pi = \text{AEZ}[E]$. Then there are efficient, explicitly given algorithms \mathcal{R} and \mathcal{S} with the following property. Let \mathcal{A} be an adversary for attacking Π . Assume it never asks a small or tiny query. Then $\mathcal{B} = \mathcal{R}(\mathcal{A})$ satisfies $\mathbf{Adv}_{\Pi, \mathcal{S}}^{\text{rae}}(\mathcal{A}) \leq 13s^2/2^{128} + \mathbf{Adv}_E^{\text{prp}}(\mathcal{B})$, where s is the total number of processed blocks, plus 2 blocks per message. Adversary \mathcal{B} makes at most $2.5s$ queries and has about the same running time as \mathcal{A} .

If one wants to accommodate small queries then we still have a provable, albeit much inferior result. Let $\text{Feistel}[r, n]$ denote an ideal r -round Feistel network on $\{0, 1\}^{2n}$. The best known provable bound for Feistel networks [44, Theorem 7] states that if an adversary makes $q \leq \frac{2^n}{128n}$ queries then $\mathbf{Adv}_{\text{Feistel}[6, n]}^{\pm \text{prp}}(\mathcal{A}) \leq \frac{8q}{2^n} + \frac{q^2}{2^{2n+1}}$. Translating this to our setting, one is bound to make at most $q \leq \frac{2^{64}}{128 \cdot 64} = 2^{51}$ small queries, and the security advantage is $q/2^{61} + 4s^2/2^{128}$. These restrictions seem to be more of the artifacts of the analysis in [44, Theorem 7] than reflecting the actual security of Feistel networks: assuming that the round functions of $\text{Feistel}[6, n]$ are instantiated from full AES, the fastest known attack, for $n \geq 64$, is still the exhaustive key search on AES.

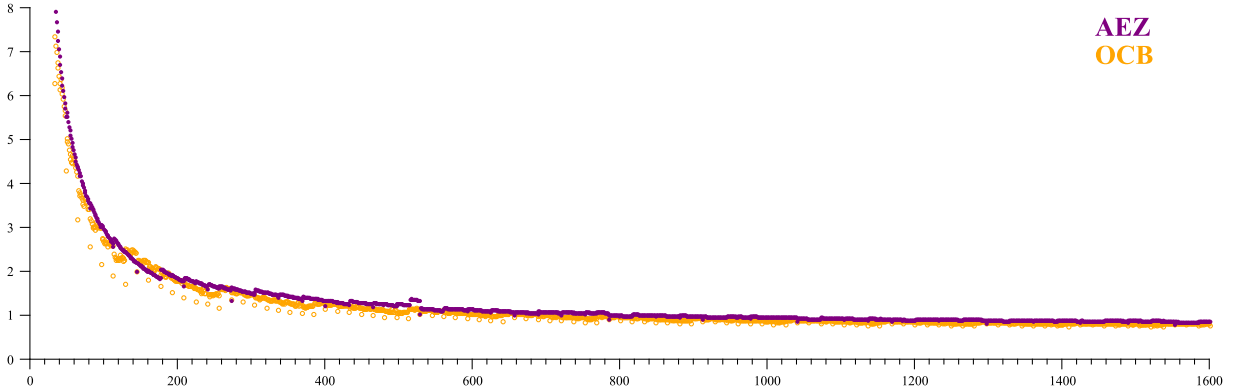


Fig. 8. AEZ vs. OCB performance. The x -axis is message length, in bytes, and the y -axis is cycles per byte (cpb). The graph is best viewed in color: solid purple circles are for AEZ; unfilled yellow circles are for OCB3 [34]. Performance of the two is close, both having peak speeds around 0.7 cpb and being similar on most shorter messages as well. The execution vehicle is an Intel Haswell processor using AES-NI.

9 Estimated Security of AEZ Itself

Consider all that would go on in enciphering a message M by the AEZ-core algorithm of AEZ[AES]. The design would seem to be excessive: each block M_i would be subjected to 30 rounds of AES (ten shared with a neighboring block)—not counting the additional AES rounds to produce the highly unpredictable, M -dependent value S , the value derived from which gets injected into the process while 20 rounds yet remain. It is in light of such apparent overkill that AEZ-core selectively prunes some of the AES calls that AEZ[AES] would perform. In particular, we prune invocations where we aim to achieve computational xor-universal hashing. We leave enough AES rounds so that each block M_i is effectively processed with 12 AES rounds, eight of these subsequent to injection of the highly-unpredictable S and four of them shared with a neighboring block. The key steps in calculating S are not pruned, nor are the TBCs used to mask u - and v -blocks.

To estimate the security of AEZ it seems appropriate to replace the $s^2/2^{128}$ term of Theorem 5 by $s^2/2^{113}$, resulting in the bound $4s^2/2^{113} + t/2^{128}$, because of the higher maximal expected differential probability of AES4 [33] compared to an ideal hash or cipher, where t is the time (including the description size) in which the adversary runs.

Moreover, we contend that the assumption that the adversary avoids asking tiny or small queries can be lifted. To justify this heuristically, consider a collection of independent, ideal, k -round Feistel networks on $\{0, 1\}^{2n}$; the round functions are all uniformly random and independent. The best attack known, due to Patarin [42], that distinguishes them from a family of independent, truly random even permutations requires at least $2^{(k-4)n}$ plaintext/ciphertext pairs. From our choice of the number of rounds, this attack needs at least 2^{72} plaintext/ciphertext pairs, and thus doesn't violate our up-to-the-birthday-bound security goal.

We emphasize that AEZ was specifically designed so that scaling-down most of its AES calls would seem safe. This is design-specific: obviously one cannot indiscriminately scale a scheme's primitives. A previous design, where AEZ-core followed the NR approach [40, 41], could not be as effectively scaled-down: there we could scale down from 3 AES per block to 1.8, whereas now we can go from 2.5 AES calls per block to just 1.

10 Software Performance

The development of AEZ has generally presumed an instruction set architecture (ISA) with round-level support for AES, such as Intel’s AES-NI or ARM’s version 8 ISA. On these systems the AES unit can be kept busy processing several AES4 computations in parallel while idle processing units handle load, store, and xor overhead. On Intel’s Haswell architecture, for example, unrelated AES rounds can issue every cycle and take seven cycles to retire, so seven parallel AES4 calculations can complete in 34 CPU cycles, while idle superscalar processing units can handle other computations. This observation has led us to design AEZ to conveniently process eight blocks at a time.

AEZ overhead beyond AES rounds has been minimized. As an example of this, our AES4 key schedule omits the final round key, allowing `aesenc`’s included xor operation to be used for other purposes. Such optimizations lead to AEZ peak speeds, on Haswell, of around 0.72 cpb—not far from the theoretical maximum of 0.63 cpb. On processors that are not superscalar or do not support AES rounds at the assembly level, we expect AEZ to continue achieving performance approximately the same as OCB, and within 10% of AES-CTR for long strings.

Fig. 8 compares the performance of AEZ and OCB on messages of all byte lengths up to 1600 bytes. The two are not only similar for long messages but for short strings too. Only when messages are shorter than 16 bytes, where AEZ-tiny increases the number of AES4 calls used, does OCB become significantly faster.

One might expect the two-pass nature of AEZ to be a performance burden because data must be dragged into cache from memory twice. We have found that modern processors, like Intel’s Haswell, have such efficient hardware prefetching that bringing data into cache twice, in a sequential streaming fashion, is not expensive at all. It requires no explicit prefetching. Encrypting 1MB on Haswell is as efficient as encrypting 32KB despite 1MB exceeding the 256KB level-2 cache. Two passes may have a more significant cost on systems with poor prefetching facilities, although this might be mitigated by software prefetching.

Another benefit of AEZ’s two passes is that the second pass is not needed to discover that a ciphertext is inauthentic, leading to message rejection costing as little as 0.28 cpb on Haswell. On long messages, approximately 2/5 of AES4 calls are performed during the first pass, which aligns perfectly with the peak times we’ve observed for encryption and fast-rejection.

All timings we have reported in this paper were gathered on a 2.9 GHz Intel Core i5-4570S CPU using its time-stamp counter to gather elapsed CPU cycles over encryption calls. Our implementation is written in C using “intrinsic” functions to access CPU-specific functionality. It was compiled using GCC 4.9 with options `-march=native -O3`. Our optimized implementation will be made publicly available and freely licensed.

Acknowledgments

Many thanks to Tom Shrimpton, who provided important interaction on RAE definitions and their implications. Liden Mu and Chris Patton proofread our specification document and did implementations that helped verify our own. We received good comments and corrections Danilo Gligoroski, Tom Ristenpart, and Yusi (James) Zhang. Thanks to Dustin Boswell for an April 2013 email on the importance of making AE easier to use, Stefan Lucks for a Jan 2012 discussion on the problem unverified plaintexts, and René Struik for an August 2013 DIAC presentation on the utility of

minimizing ciphertext expansion. Thanks to Terence Spies for catalyzing the idea of unifying AE and blockciphers both in definition and schemes.

Hoang was supported by NSF grants CNS-0904380, CCF-0915675, CNS-1116800 and CNS-1228890; Krovetz was supported by NSF grant CNS-1314592; and Rogaway was supported by NSF grants CNS-1228828 and CNS-1314885. Many thanks to the NSF for their continuing support. Part of this work was done when Hoang was working at UC San Diego.

References

1. E. Andreeva, A. Bogdanov, A. Luykx, B. Mennink, N. Mouha, and K. Yasuda. How to securely release unverified plaintext in authenticated encryption. Cryptology ePrint report 2014/144. Feb 25, 2014.
2. E. Andreeva, A. Bogdanov, A. Luykx, B. Mennink, E. Tischhauser, and K. Yasuda. Parallelizable and authenticated online ciphers. *ASIACRYPT 2013*. LNCS 8269, Springer, pp. 424–443, 2013.
3. B. Barak, Y. Dodis, H. Krawczyk, O. Pereira, K. Pietrzak, F. Standaert, and Y. Yu. Leftover hash lemma, revisited. *CRYPTO 2011*. LNCS 6841, Springer, pp. 1–20, 2011.
4. M. Bellare, A. Boldyreva, L. Knudsen, and C. Namprempre. Online ciphers and the Hash-CBC construction. *CRYPTO 2001*. LNCS 2139, pp. 292–309, 2001. Also Cryptology ePrint Archive 2007/197.
5. M. Bellare and P. Rogaway. On the construction of variable-input-length ciphers. *FSE 1999*. LNCS 1636, Springer, pp. 321–344, 1999.
6. M. Bellare and P. Rogaway. Encode-then-encipher encryption: how to exploit nonces or redundancy in plaintexts for efficient cryptography. *ASIACRYPT 2000*. LNCS 1976, Springer, pp. 317–330, 2000.
7. M. Bellare, P. Rogaway, and T. Spies. The FFX mode of operation for format-preserving encryption. Draft 1.1. Submission to NIST. Feb 20, 2010.
8. D. Bernstein. Cryptographic competitions: CAESAR call for submissions, final (2014.01.27). Available at <http://competitions.cr.yp.to/caesar-call.html>.
9. J. Black and M. Cochran. MAC reforgeability. LNCS 5665, Springer, FSE 2009, pp. 345–362, 2009.
10. J. Black and P. Rogaway. Ciphers with arbitrary finite domains. *CT-RSA 2002*. LNCS 2271, Springer, pp. 114–130, 2002.
11. A. Boldyreva, J. Degabriele, K. Paterson, and M. Stam. On symmetric encryption with distinguishable decryption failures. Cryptology ePrint Report 2013/433, 2013.
12. D. Chakraborty and M. Nandi. An improved security bound for HCTR. *FSE 2008*. LNCS 5086, Springer, pp. 289–302, 2008.
13. D. Chakraborty and P. Sarkar. HCH: A new tweakable enciphering scheme using the hash-encrypt-hash approach. *IEEE Transactions on Information Theory*, 54(4), pp. 1683–1699, 2008.
14. D. Chakraborty and P. Sarkar. A new mode of encryption providing a tweakable strong pseudorandom permutation. *FSE 2006*. LNCS 4047, Springer, pp. 293–309, 2006.
15. J. Daemen and V. Rijmen. A new MAC construction ALRED and a specific instance ALPHA-MAC. *Fast Software Encryption*. LNCS 3557, Springer, pp. 1–17, 2005.
16. J. Daemen and V. Rijmen. The Pelican MAC function. Cryptology ePrint report 2005/088. 2005.
17. Y. Dodis, R. Gennaro, J. Håstad, H. Krawczyk, and T. Rabin. Randomness extraction and key derivation using the CBC, cascade and HMAC modes. *CRYPTO 2004*. LNCS 3152, Springer, pp. 494–510, 2004.
18. M. Dworkin. Recommendation for block cipher modes of operation: methods for format-preserving encryption. NIST Special Publication 800-38G: Draft. July 2013.
19. N. Ferguson. Authentication weaknesses in GCM. Manuscript. May 20, 2005.
20. S. Halevi. EME*: extending EME to handle arbitrary-length messages with associated data. *INDOCRYPT 2004*. LNCS 3348, Springer, pp. 315–327, 2004.
21. J. Katz and M. Yung. Unforgeable encryption and chosen ciphertext secure modes of operation. *FSE 2000*, LNCS 1978, Springer, pp. 284–299, 2000.
22. R. Fisher and F. Yates. *Statistical tables for biological, agricultural and medical research*. London: Oliver & Boyd, 1938.
23. E. Fleischmann, C. Forler, S. Lucks, and J. Wenzel. McOE: A family of almost foolproof on-line authenticated encryption schemes. *FSE 2012*. LNCS 7549, Springer, pp. 196–215, 2011. Also Cryptology ePrint Report 211/644 (29 Nov 2011; revised 5 Dec 2013).

24. P. Fouque, A. Joux, G. Martinet, and F. Valette. Authenticated on-line encryption. *SAC 2003*. LNCS 3006, pp. 145–159, 2004.
25. S. Halevi. EME*: extending EME to handle arbitrary-length messages with associated data. *INDOCRYPT 2004*. LNCS 3347, Springer, pp. 315–327, 2004.
26. S. Halevi. Invertible universal hashing and the TET encryption mode. Cryptology ePrint report 2007/014.
27. S. Halevi and P. Rogaway. A parallelizable enciphering mode. *CT-RSA 2004*. LNCS 2964, Springer, pp. 292–304, 2004.
28. S. Halevi and P. Rogaway. A tweakable enciphering mode. *CRYPTO 2003*. LNCS 2729, Springer, pp. 482–499, 2003.
29. J. Håstad, R. Impagliazzo, L. Levin, and M. Luby. Construction of a pseudo-random generator from any one-way function. *SIAM Journal on Computing*, 28(4), pp. 1364–1396, 1999.
30. IEEE. 1619.2-2010 – IEEE standard for wide-block encryption for shared storage media. IEEE press, 2010.
31. R. Impagliazzo and S. Rudich. Limits on the provable consequences of one-way permutations. *STOC 1989*, pp. 44–61, 1989.
32. B. Kaliski, R. Rivest, and A. Sherman. Is DES a pure cipher? (Results of more cycling experiments on DES). *CRYPTO 85*. LNCS 218, Springer, pp. 212–226, 1986.
33. L. Keliher and J. Sui. Exact maximum expected differential and linear probability for two-round Advanced Encryption Standard. *IET Information Security*, 1(2), pp. 53–57, 2007.
34. T. Krovetz and P. Rogaway. The software performance of authenticated-encryption modes. *FSE 2011*. LNCS 6733, Springer, pp. 306–327, 2011.
35. M. Liskov, R. Rivest, and D. Wagner. Tweakable block ciphers. *CRYPTO 2002*. LNCS 2442, Springer, pp. 31–46, 2002.
36. D. McGrew and S. Fluhrer. The security of the extended codebook (XCB) mode of operation. *SAC 2007*. LNCS 4876, Springer, pp. 311–327, 2007.
37. K. Minematsu. Parallelizable rate-1 authenticated encryption from pseudorandom functions. *EUROCRYPT 2014*. LNCS 8441, Springer, pp. 275–292, 2014.
38. K. Minematsu and Y. Tsunoo. Provably secure MACs from differentially-uniform permutations and AES-based implementations. *FSE 2006*. LNCS 4047, Springer, pp. 226–241, 2006.
39. M. Nandi. Improving upon HCTR and matching attacks for Hash-Counter-Hash approach. Cryptology ePrint report 2008/090. Feb 28, 2008.
40. M. Naor and O. Reingold. On the construction of pseudo-random permutations: Luby-Rackoff revisited. *Journal of Cryptology*, 12(1), pp. 29–66, 1999.
41. M. Naor and O. Reingold. The NR mode of operation. Undated manuscript realizing the mechanism of [40].
42. J. Patarin. Generic attacks on Feistel schemes. *ASIACRYPT 2001*. LNCS 2248, Springer, pp. 222–238, 2001. Also see Cryptology ePrint report 2008/036.
43. S. Patel, Z. Ramzan, and G. Sundaram. Efficient constructions of variable-input-length block ciphers. *SAC 2004*. LNCS 3357, Springer, 2004.
44. J. Patarin. Security of balanced and unbalanced Feistel schemes with linear non equalities. Cryptology ePrint report 2010/293. May 2010.
45. J. Patarin. Security of random Feistel schemes with 5 or more rounds. *CRYPTO 2004*. LNCS 3152, Springer, pp. 106–122, 2004.
46. J. Patarin, B. Gittins, and J. Treger. Increasing block sizes using Feistel networks: the example of the AES. *Cryptography and Security: From Theory to Applications*. LNCS 6805, Springer, pp. 67–82, 2012.
47. R. Reyhanitabar and D. Vizár. Careful with misuse resistance of online AEAD. Unpublished manuscript distributed on the `crypto-competitions` mailing list. August 24, 2014.
48. P. Rogaway. Authenticated-encryption with associated-data. *ACM CCS 2002*. ACM Press, pp. 98–107, 2002.
49. P. Rogaway. Efficient instantiations of tweakable blockciphers and refinements to modes OCB and PMAC. *ASIACRYPT 2004*. LNCS 3329, Springer, pp. 16–31, 2004.
50. P. Rogaway, M. Bellare, J. Black, and T. Krovetz. OCB: A block-cipher mode of operation for efficient authenticated encryption. *ACM CCS 2001*, pp. 196–205.
51. P. Rogaway and T. Shrimpton. A provable-security treatment of the key-wrap problem. *EUROCRYPT 2006*. LNCS 4004, Springer, pp. 373–390, 2006. Also Cryptology ePrint Report 2006/221, retitled Deterministic authenticated-encryption: a provable-security treatment of the key-wrap problem.
52. P. Sarkar. Efficient tweakable enciphering schemes from (block-wise) universal hash functions. Cryptology ePrint report 2008/004.

53. P. Sarkar. Improving upon the TET mode of operation. *Information Security and Cryptology (ICISC 2007)*. LNCS 4817, Springer, pp. 180–192, 2007.
54. P. Sarkar. Tweakable enciphering schemes using only the encryption function of a block cipher. *Cryptology ePrint report 2009/216*.
55. R. Schroepfel. Hasty Pudding Cipher Specification. AES candidate submitted to NIST. June 1998 (revised May 1999). <http://richard.schroepfel.name/hpc/hpc-spec>
56. T. Shrimpton and S. Terashima. A modular framework for building variable-input-length tweakable ciphers. *ASIACRYPT (1) 2013*. LNCS 8269, Springer, pp. 405–423, 2013.
57. M. Simplicio, P. Barbuda, P. Barreto, T. Carvalho, and C. Margi. The MARVIN message authentication code and the LETTERSOUP authenticated encryption scheme. *Security and Communications Networks*, 2(2), pp. 165–180, 2009.
58. M. Simplicio and P. Barreto. Revisiting the security of the ALRED design and two of its variants: Marvin and LetterSoup. *IEEE Transactions on Information Theory*, 58(9), pp. 6223–6238, 2012.
59. R. Struik. AEAD ciphers for highly constrained networks. DIAC 2013 presentation. Aug 13, 2013.
60. P. Wang, D. Feng, C. Lin, and W. Wu. Security of truncated MACs. *Inscrypt 2008*. LNCS 5487, Springer, pp. 96–114, 2009.
61. P. Wang, D. Feng, and W. Wu. HCTR: a variable-input-length enciphering mode. *Information Security and Cryptology (ICISC 2005)*. LNCS 3822, Springer, pp. 175–188, 2005.

A More on Related Work

RAE and AEZ build on a large body of related work. While we have summarized much of this throughout this paper, here we give some additional context and high points.

Blockciphers accommodating truly arbitrary inputs were first realized by Schroepfel’s Hasty Pudding Cipher (HPC) [55]. Ahead of its time, the work not only built a blockcipher on all of $\{0, 1\}^*$, but also provided it a tweak. If one were to first overcome the problem that HPC’s tweak is limited in length, it could be used with the EtE construction to make an RAE scheme.

The problem of constructing from conventional blockciphers those with arbitrary or near-arbitrary domains was first identified Bellare and Rogaway [5], who wanted to construct these objects with a conventional-looking mode. But the mechanism they suggested was somewhat slow, was limited to a domain of $(\{0, 1\}^n)^+$, and only achieves conventional (not strong) PRP security.

In a follow-up paper [6] the same authors evidenced the utility of arbitrary-input blockciphers by explaining how semantic security could be achieved by enciphering messages with novelty, and they showed how how authenticity could be achieve by enciphering messages with redundancy (this time using a *strong* PRP). These observations formed the basis for our work.

Around the same time as the last two work, Naor and Reingold (NR) constructed a blockcipher on $(\{0, 1\}^n)^+$ by sandwiching a layer of ECB between layers of a “blockwise-universal” hashing [40, 41]. The approach came to be used in many proposals, including XCB [36], which was standardized in IEEE 1619.2 [30].

The other method inspiring further wide-block blockciphers was EME [27], which involves two layers of blockcipher-based enciphering and a light layer of mixing in between. A follow-on design, EME2 [20], become the other wide-block blockcipher of 1619.2 [30]. Both it and XCB are tweakable and operate on a message space of $\{0, 1\}^{\geq n}$. EME/EME2 provides the starting point for AEZ-core.

As for extending blockciphers to short blocks, a different line of work was begun [10]. *Format-preserving encryption* aimed to deal not only with small domains but also those defined as arbitrary finite sets, sets of numbers $[0..N - 1]$, or strings over arbitrary alphabets. Adapting Feistel designs to arbitrary alphabets, realizations of FFX [7], now a draft NIST standard [18], would form the basis of AEZ-tiny.

Meanwhile, notions of AE were appearing. Probabilistic versions came first [6, 21], then a nonce-based version [50], then AD finally appeared [49]. Next the MRAE goal—RAE’s closest definition counterpart—was defined [51]. The main motivation for that work was to minimize the damage that could be done by nonce-reuse.

Other authors had the same concern but weren’t willing to use two-pass schemes. Fleischmann *et. al* [23] built on Bellare *et. al* [4] to define a security notion for online-AE intended to confer some lower level of nonce-reuse misuse resistance. The approach has gained popularity—many CAESAR submissions follow it, especially after COPA [2] made clear that one could achieve this weakened flavor of nonce-reuse misuse-resistance with a parallelizable scheme. The RAE definition goes a different direction, strengthening instead of weakening the original MRAE definition.

Following up on directions from prior work [11, 23, 24], AE security in the face of decryption-algorithm leakage was studied by Andreeva *et. al* [1] in work concurrent with our own. A principle motivation for those authors has been to express when it is OK for an online decryption algorithm to be incrementally releasing unverified plaintext. For us, this is a direction not taken, for such leakage can never be generically harmless [47]. In effect, leaking equality of message prefixes is leaking an enormous amount of information.

Ferguson made clear early on that AE algorithms could fail badly when tags are too short [19]. Still, no definitions for AE security were ever offered appropriate to the short-tag setting. But the general concern for making short MACs work well goes back to Black and Cochran [9] and Wang *et. al* [60].

Some examples of using AES4 where AES itself would do include ALRED, LETTERSOUP, MARVIN, and Pelican [15, 16, 57]. These inspired our predilection to cut certain AES rounds even when provable security couldn’t promise this was fine. The approach should not be confused with that of Minematsu and Tsunoo [38], where AES4 provably *does* suffice for the protocol devised [38]. The approach leverages the low MEDP for AES4, a line of work culminating in the bound of Keliher and Sui [33].

Many authors have proposed ideas to eliminate use of the inverse-direction of a blockcipher in modes that previously needed this. The method we use in AEZ is inspired by Minematsu’s OTR [37].

The CAESAR competition [8], organized by Dan Bernstein, was the proximal motivation to define RAE and to try to develop a nice scheme for achieving it.

B Deferred Proofs

B.1 Proof of Theorem 1

It suffices to show that $|\Pr[\mathcal{A}^{\text{Ideal}_\Pi} \Rightarrow 1] - \Pr[\mathcal{A}^{\text{PRI}_\Pi} \Rightarrow 1]| \leq (r^2 + r)/|\Sigma|^{\lambda+m_{\min}+1} + 2q/|\Sigma|^\lambda$. Without loss of generality, assume that $q \leq |\Sigma|^{\lambda-1}$; otherwise the claim is trivial. Consider games G_1 – G_4 in Fig. 9. Game G_1 corresponds to game **Ideal** $_\Pi$ and game G_4 corresponds to game **PRI** $_\Pi$. We explain the game chain up to the terminal one. Game G_2 is identical to game G_1 , except that in procedure **Enc**, it ensures that ciphertexts C are distinct. Partition the encryption queries based on the nonce, the associated data, and the size of the message. Suppose that in game G_1 we have p partitions of size $s_1, \dots, s_p \geq 1$. Games G_1 and G_2 are identical-until-bad, and thus

$$\begin{aligned} |\Pr[\mathcal{A}^{G_1} \Rightarrow 1] - \Pr[\mathcal{A}^{G_2} \Rightarrow 1]| &\leq \Pr[\mathcal{A}^{G_1} \text{ sets bad}] \\ &\leq \sum_{i=1}^p \frac{s_i(s_i - 1)}{|\Sigma|^{m_{\min} + \lambda + 1}} = \sum_{i=1}^p \frac{(s_i - 1)^2 + (s_i - 1)}{|\Sigma|^{m_{\min} + \lambda + 1}} \leq \frac{r^2 + r}{|\Sigma|^{m_{\min} + \lambda + 1}}, \end{aligned}$$

proc Enc(N, A, M) Games G_1 / G_2 $\ell \leftarrow M $; $C \leftarrow \Sigma^{\ell+\lambda}$ if $C \in \text{Ran}_{N,A,\ell}$ then bad \leftarrow true; $C' \leftarrow \Sigma^{\ell+\lambda} \setminus \text{Ran}_{N,A,\ell}$ $\text{Ran}_{N,A,\ell} \leftarrow \text{Ran}_{N,A,\ell} \cup \{C\}$ $\text{Dom}_{N,A} \leftarrow \text{Dom}_{N,A} \cup \{(M, \mathbf{0}^\lambda)\}$ return C proc Dec(N, A, λ, C) if $ C < \lambda$ then return \perp $\ell \leftarrow C - \lambda$; $(M, v) \leftarrow (\Sigma^\ell \times \Sigma^\lambda) \setminus \text{Dom}_{N,A}$ $\text{Dom}_{N,A} \leftarrow \text{Dom}_{N,A} \cup \{(M, v)\}$ return \perp	proc Enc(N, A, M) Games G_3 / G_4 $\ell \leftarrow M $; $C \leftarrow \Sigma^{\ell+\lambda}$ $\text{Dom}_{N,A} \leftarrow \text{Dom}_{N,A} \cup \{(M, \mathbf{0}^\lambda)\}$ return C proc Dec(N, A, C) if $ C < \lambda$ then return \perp $\ell \leftarrow C - \lambda$ $(M, v) \leftarrow (\Sigma^\ell \times \Sigma^\lambda) \setminus \text{Dom}_{N,A}$ $\text{Dom}_{N,A} \leftarrow \text{Dom}_{N,A} \cup \{(M, v)\}$ if $v = \mathbf{0}^\lambda$ then bad \leftarrow true; return M return \perp
--	--

Fig. 9. Games used in the proof of Theorem 1. Here $\mathbf{0}$ is a canonical element of Σ . Games G_2 and G_4 contain the corresponding boxed statements, but games G_1 and G_3 do not.

the last inequality is due to the fact that $(s_1 - 1) + \dots + (s_p - 1) = r$. Game G_3 is a simplified version of game G_2 ; the change is conservative. Game G_4 is identical to game G_3 , except that in procedure Dec, it samples a λ -character string v and returns a non- \perp answer if $v = \mathbf{0}^\lambda$, where $\mathbf{0}$ is a canonical point in Σ . Let L' be the multiset of $|C|$ in \mathcal{A} 's decryption queries in game G_4 , and let L be the multiset $\{\ell \mid \ell \geq 0 \text{ and } \ell + \lambda \in L'\}$. Then

$$\begin{aligned}
|\Pr[\mathcal{A}^{G_3} \Rightarrow 1] - \Pr[\mathcal{A}^{G_4} \Rightarrow 1]| &\leq \Pr[\mathcal{A}^{G_3} \text{ sets bad}] \leq \sum_{\ell \in L} \frac{|\Sigma|^\ell}{|\Sigma|^{\ell+\lambda} - q} \\
&= \sum_{\ell \in L} \frac{1}{|\Sigma|^\lambda - (q/|\Sigma|^\ell)} \\
&\leq \sum_{\ell \in L} \frac{1}{|\Sigma|^\lambda - q} \leq \frac{q}{|\Sigma|^\lambda - q} \leq \frac{2q}{|\Sigma|^\lambda};
\end{aligned}$$

the last inequality is due to the assumption that $q \leq |\Sigma|^{\lambda-1}$. Summing up,

$$\begin{aligned}
|\Pr[\mathcal{A}^{\text{Ideal}_\Pi} \Rightarrow 1] - \Pr[\mathcal{A}^{\text{PRI}_\Pi} \Rightarrow 1]| &\leq \sum_{i=1}^3 |\Pr[\mathcal{A}^{G_i} \Rightarrow 1] - \Pr[\mathcal{A}^{G_{i+1}} \Rightarrow 1]| \\
&\leq \frac{r^2 + r}{|\Sigma|^{\lambda+m_{\min}+1}} + \frac{2q}{|\Sigma|^\lambda}
\end{aligned}$$

as claimed.

B.2 Proof of Theorem 2

The reduction \mathcal{R} creates from \mathcal{A} the adversary \mathcal{B} as follows. It runs \mathcal{A} . When the latter makes an encryption query (N, A, λ, M) , if $v(M) = 1$ then the former sends the same query to its encryption oracle and returns the answer to \mathcal{A} ; otherwise it returns \perp . When \mathcal{A} makes a query (N, A, λ, C) , adversary \mathcal{B} sends the same query to its decryption oracle to get M . If $|M| = |C| - \lambda$ and $v(M) \neq 1$ then it returns $\mathbf{0} \parallel M$ to \mathcal{A} , where $\mathbf{0}$ is a canonical point in Σ . Otherwise, it returns M . Finally, it outputs the same guess as \mathcal{A} .

For any query (N, A, λ, C) that it receives, S' stores $(N, A, \lambda, |C|)$ in a set L_λ . It also maintains, for each (N, A, λ, ℓ) in L_λ , a set $B_{N,A,\lambda,\ell}$. Initially, $B_{N,A,\lambda,\ell} = \Sigma^{\ell-\lambda} \setminus \mathcal{M}_v$. The simulator S' works by running the simulator S . For each query (N, A, λ, C) , the simulator S' tosses a biased coin, the head will land with probability $\frac{|B_{N,A,\lambda,\ell}|}{|B_{N,A,\lambda,\ell}| + (|\Sigma|^\ell - |\Sigma|^{\ell-\lambda})}$, where $\ell = |C|$. If the head shows up, S' will sample $M \leftarrow B_{N,A,\lambda,\ell}$, remove M from $B_{N,A,\lambda,\ell}$, and return M . Otherwise, it will run S on query (N, A, λ, C) and output whatever S returns. Then

$$\begin{aligned} \Pr[\mathcal{A}^{\mathbf{REAL}_{\Pi v, S'}} \Rightarrow 1] &= \Pr[\mathcal{B}^{\mathbf{REAL}_{\Pi, S}} \Rightarrow 1], \text{ and} \\ \Pr[\mathcal{A}^{\mathbf{RAE}_{\Pi v, S'}} \Rightarrow 1] &= \Pr[\mathcal{B}^{\mathbf{RAE}_{\Pi, S}} \Rightarrow 1]. \end{aligned}$$

Subtracting, we'll get $\mathbf{Adv}_{\Pi, S}^{\text{rae}}(\mathcal{B}) = \mathbf{Adv}_{\Pi v, S'}^{\text{rae}}(\mathcal{A})$.

B.3 Proof of Theorem 3

The reduction \mathcal{R} creates from \mathcal{A} the adversary \mathcal{B} as follows. It runs \mathcal{A} . Whenever \mathcal{A} makes an encryption query (N, A, λ, M) , adversary \mathcal{B} sends $(T, \text{Encode}_\lambda(M))$ to its left oracle, with $T = (N, A, \lambda)$, and returns the answer to \mathcal{A} . When \mathcal{A} makes a decryption query (N, A, λ, C) , adversary \mathcal{B} sends (T, C) , with $T = (N, A, \lambda)$ to its right oracle to get answer X , and then returns $\text{Decode}_\lambda(X)$ to \mathcal{A} . Finally, it outputs the same guess as \mathcal{A} .

Let $\Pi = \text{EtE}[\text{Encode}, \text{Perm}(\mathcal{T}, \Sigma^*)]$ be the variant of $\text{EtE}[\text{Encode}, \tilde{\mathbb{E}}]$ in which $\tilde{\mathbb{E}}_K$ is replaced by an ideal tweakable, length-preserving random permutation $\tilde{\pi} : \mathcal{T} \times \Sigma^* \rightarrow \Sigma^*$. It suffices to build a simulator S such that $\mathbf{Adv}_{\Pi, S}^{\text{rae}}(\mathcal{A}) = 0$ for any adversary \mathcal{A} . Wlog, assume that the simulator is given only queries (N, A, λ, C) of $\lambda > 0$, and assume that the adversary never repeats its queries. For each $\lambda \in \mathbb{Z}^+$ and each $\ell \geq \lambda$, let $V_{\ell, \lambda} = \Sigma^\ell \setminus R_\lambda$, where R_λ is the range of $\text{Encode}_\lambda(\cdot)$. Then $|V_{\ell, \lambda}| = |\Sigma|^\ell - |\Sigma|^{\ell-\lambda} \geq \frac{1}{2}|\Sigma|^\ell$. For each query (N, A, λ, C) it receives, the simulator S stores $(N, A, \lambda, |C|)$ in a set L_λ . It also maintains, for each $(N, A, \ell, \lambda) \in L_\lambda$, an (initially empty) set $B_{N,A,\ell,\lambda}$. On input (N, A, λ, C) , if $|B_{N,A,\ell,\lambda}| < |V_{\ell, \lambda}|$ then S picks $M \leftarrow V_{\ell, \lambda} \setminus B_{N,A,\ell,\lambda}$, adds M to $B_{N,A,\ell,\lambda}$, and returns M , where $\ell = |C|$. Otherwise, the simulator returns \perp . Then $\mathbf{Adv}_{\Pi, S}^{\text{rae}}(\mathcal{A}) = 0$.

What's left is to show how to implement the sampling $M \leftarrow V_{\ell, \lambda} \setminus B_{N,A,\ell,\lambda}$ efficiently, for $\ell > 5$. If $|V_{\ell, \lambda} \setminus B_{N,A,\ell,\lambda}| > \frac{1}{4}|\Sigma|^\ell$ then S keeps sampling in Σ^ℓ until it hits a point $M \in V_{\ell, \lambda} \setminus B_{N,A,\ell,\lambda}$. The expected number of sampling operations is $O(1)$, and each sampling runs in $O(\ell + \lambda)$ time. The set $B_{N,A,\ell,\lambda}$ is implemented via a hash, and thus the amortized cost of checking if $M \in V_{\ell, \lambda} \setminus B_{N,A,\ell,\lambda}$ is $O(\ell + \lambda)$. At the moment $|V_{\ell, \lambda} \setminus B_{N,A,\ell,\lambda}| = \frac{1}{4}|\Sigma|^\ell$, the simulator stores the elements of $V_{\ell, \lambda} \setminus B_{N,A,\ell,\lambda}$ in an array $H_{N,A,\ell,\lambda}$, and then performs a Fisher–Yates shuffle [22] (commonly known as Knuth shuffle) over $H_{N,A,\ell,\lambda}$. The running time of this shuffling is $O(|\Sigma|^\ell \cdot (\ell + \lambda))$, but it's done after $|V_{\ell, \lambda}| - \frac{1}{4}|\Sigma|^\ell \geq \frac{1}{4}|\Sigma|^\ell$ invocations of S , and thus the amortized cost is only $O(\ell + \lambda)$. If $|V_{\ell, \lambda} \setminus B_{N,A,\ell,\lambda}| \leq \frac{1}{4}|\Sigma|^\ell$, since the array $H_{N,A,\ell,\lambda}$ is already built, S picks $M \leftarrow H_{N,A,\ell,\lambda}[m]$, where $m = \lfloor \frac{1}{4}|\Sigma|^\ell \rfloor + 1 - |V_{\ell, \lambda} \setminus B_{N,A,\ell,\lambda}|$.

B.4 Proof of Theorem 4

The reduction \mathcal{R} creates from adversary \mathcal{A} the adversary \mathcal{B} as follows. For each encryption query M (respectively, decryption query C) of \mathcal{A} , adversary \mathcal{B} runs the encryption of AEZ-core on M (respectively, decryption of AEZ-core on C), but each call to $f_K(T, x)$ is replaced by querying (T, x) to the oracle. It then outputs the same guess as \mathcal{A} . Let $\text{Func}(\mathcal{T}, n)$ be the set of all functions

$\rho : \mathcal{T} \times \{0, 1\}^n \rightarrow \{0, 1\}^n$. Let $\text{AEZ-core}[\text{Func}(\mathcal{T}, n)]$ denote the ideal variant of $\text{AEZ-core}[\mathbb{E}]$, where f_K is replaced by $\rho \leftarrow \text{Func}(\mathcal{T}, n)$. It suffices to show that

$$\mathbf{Adv}_{\text{AEZ-core}[\text{Func}(\mathcal{T}, n)]}^{\pm \text{prp}}(\mathcal{A}) \leq \frac{2\sigma^2}{2^n} \quad (1)$$

We now prove claim (1) for an even computationally unbounded adversary \mathcal{A} . Without loss of generality, assume that \mathcal{A} is deterministic. Assume that $\sigma \leq 2^n$; otherwise the theorem is trivial. Assume further that \mathcal{A} doesn't make redundant queries: it never repeats a prior query, once it makes an encryption query (T, M) to get C then it won't query (T, C) to the decryption oracle, and likewise, once it makes a decryption query (T, C) to get M then it won't query (T, M) to the encryption oracle. Let $q \leq 2\sigma$ be the number of queries of \mathcal{A} and let q_i be the number of queries that have at least $2i+2$ full blocks. We claim that $2 \sum_{i \in \mathbb{N}} q_i \leq \sigma$. Let \mathcal{P} be a $q \times \sigma$ matrix. For each $j \leq q$, let ℓ_j be the length of the j th query and color the first $2 \cdot \lfloor \ell_j / 2n \rfloor$ entries of the j th column of \mathcal{P} . Then the total number of colored entries in \mathcal{P} is

$$\sum_{j=1}^q 2 \cdot \left\lfloor \frac{\ell_j}{2n} \right\rfloor \leq \sum_{j=1}^q \left\lceil \frac{\ell_j}{n} \right\rceil = \sigma.$$

On the other hand, each q_i is the number of colored entries in the $(2i+1)$ th row of \mathcal{P} , and also the number of colored entries in the $(2i+2)$ th row. Hence $2 \sum_{i \in \mathbb{N}} q_i$ is the number of colored entries of \mathcal{P} , justifying the claim above.

Consider games G_1 and G_2 in Fig. 10. Adversary can call $\text{ENC}(\cdot)$ for encryption queries, and $\text{DEC}(\cdot)$ for decryption queries. Game G_1 is the random game: ENC and DEC implements π and π^{-1} , where π is an ideal random length-preserving permutation on $\{0, 1\}^{\geq 2n}$. In game G_2 , for each $\text{ENC}(M)$ query, we output a uniformly random $C = (C_1, C'_1, \dots, C_m, C'_m, C_u, C_v, C_x, C_y)$ of length $|M|$ subject to the following conditions:

- $C'_i \neq M'_i$ and C'_i is also different from \tilde{M}'_i and \tilde{C}'_i produced by any prior (\tilde{M}, \tilde{C}) , for every $i \leq m$.
- $C_y \neq M_y$ and C_y is also different from \tilde{M}_y and \tilde{C}_y produced by any prior (\tilde{M}, \tilde{C}) .

Likewise, for each $\text{DEC}(C)$ query, we output a uniformly random $M = (M_1, M'_1, \dots, M_m, M'_m, M_u, M_v, M_x, M_y)$ of length $|C|$ subject to the conditions that:

- $M'_i \neq C'_i$ and M'_i is also different from \tilde{M}'_i and \tilde{C}'_i produced by any prior (\tilde{M}, \tilde{C}) , for every $i \leq m$.
- $M_y \neq C_y$ and M_y is also different from \tilde{M}_y and \tilde{C}_y produced by any prior (\tilde{M}, \tilde{C}) .

Since the two games G_1 and G_2 are identical-until-bad, and thus

$$\Pr[\mathcal{A}^{G_1} \Rightarrow 0] - \Pr[\mathcal{A}^{G_2} \Rightarrow 0] \leq \Pr[\mathcal{A}^{G_1} \text{ sets bad}] \leq \sum_{i \in \mathbb{N}} \frac{2q_i(2q_i - 1)}{2^{n+1}} \leq \frac{2q}{2^n} \sum_{i \in \mathbb{N}} q_i \leq \frac{\sigma q}{2^n}.$$

On the other hand, because

$$\begin{aligned} \mathbf{Adv}_{\text{AEZ-core}[\text{Func}(\mathcal{T}, n)]}^{\pm \text{prp}}(\mathcal{A}) &= \Pr[\mathcal{A}^{G_1} \Rightarrow 0] - \Pr[\mathcal{A}^{H_2} \Rightarrow 0] \\ &\leq \Pr[\mathcal{A}^{G_1} \Rightarrow 0] - \Pr[\mathcal{A}^{G_2} \Rightarrow 0] + \Pr[\mathcal{A}^{G_2} \Rightarrow 0] - \Pr[\mathcal{A}^{H_2} \Rightarrow 0], \end{aligned}$$

<pre> proc ENC(M) $(M_1, M'_1, \dots, M_m, M'_m, M_u, M_v, M_x, M_y) \leftarrow M$ $\text{Dom}_y \leftarrow \text{Dom}_y \cup \{M_y\}; C \leftarrow \{0, 1\}^{ M }$ $(C_1, C'_1, \dots, C_m, C'_m, C_u, C_v, C_x, C_y) \leftarrow C$ for $i = 1$ to m do $\text{Dom}_i \leftarrow \text{Dom}_i \cup \{M'_i\}$ if $C'_i \in \text{Dom}_i$ then bad \leftarrow true; $C'_i \leftarrow \{0, 1\}^n \setminus \text{Dom}_i$ $\text{Dom}_i \leftarrow \text{Dom}_i \cup \{C'_i\}$ if $C_y \in \text{Dom}_y$ then bad \leftarrow true; $C_y \leftarrow \{0, 1\}^n \setminus \text{Dom}_y$ $C \leftarrow (C_1, C'_1, \dots, C_m, C'_m, C_u, C_v, C_x, C_y)$ $\text{Dom}_y \leftarrow \text{Dom}_y \cup \{C_y\}$; return C </pre>	<pre> proc DEC(C) Games G_1 / G_2 $(C_1, C'_1, \dots, C_m, C'_m, C_u, C_v, C_x, C_y) \leftarrow C$ $\text{Dom}_y \leftarrow \text{Dom}_y \cup \{C_y\}; M \leftarrow \{0, 1\}^{ C }$ $(M_1, M'_1, \dots, M_m, M'_m, M_u, M_v, M_x, M_y) \leftarrow M$ for $i = 1$ to m do $\text{Dom}_i \leftarrow \text{Dom}_i \cup \{C'_i\}$ if $M'_i \in \text{Dom}_i$ then bad \leftarrow true; $M'_i \leftarrow \{0, 1\}^n \setminus \text{Dom}_i$ $\text{Dom}_i \leftarrow \text{Dom}_i \cup \{M'_i\}$ if $M_y \in \text{Dom}_y$ then bad \leftarrow true; $M_y \leftarrow \{0, 1\}^n \setminus \text{Dom}_y$ $M \leftarrow (M_1, M'_1, \dots, M_m, M'_m, M_u, M_v, M_x, M_y)$ $\text{Dom}_y \leftarrow \text{Dom}_y \cup \{M_y\}$; return M </pre>
--	--

Fig. 10. Games G_1 and G_2 in the proof of Theorem 4. Game G_2 includes the corresponding boxed statement, but game G_1 does not.

<pre> proc VALIDATE(M, C, cmd) $(M_1, M'_1, \dots, M_m, M'_m, M_u, M_v, M_x, M_y) \leftarrow M; (C_1, C'_1, \dots, C_m, C'_m, C_u, C_v, C_x, C_y) \leftarrow C; X, Y \leftarrow 0^n$ for $i = 1$ to m do if $\text{cmd} = \text{'enc'}$ then $V_i \leftarrow \rho_{a,i}(M'_i) \oplus M_i$ if $(H[i, M_i M'_i] = \perp) \wedge (V_i \in \text{Dom}_a)$ then bad \leftarrow true else $\text{Dom}_a \leftarrow \text{Dom}_a \cup \{V_i\}$ $H[i, M_i M'_i] \leftarrow X_i \leftarrow \rho_a(V_i) \oplus M'_i; H[i, C_i C'_i] \leftarrow Y_i \leftarrow X_i \oplus V_i \oplus \rho_{a,i}(C'_i) \oplus C_i; U_i \leftarrow \rho_{a,i}(C'_i) \oplus C_i$ if $U_i \in \text{Dom}_a$ then bad \leftarrow true else $\text{Dom}_a \leftarrow \text{Dom}_a \cup \{U_i\}$ else $U_i \leftarrow \rho_{a,i}(C'_i) \oplus C_i$ if $(H[i, C_i C'_i] = \perp) \wedge (U_i \in \text{Dom}_a)$ then bad \leftarrow true else $\text{Dom}_a \leftarrow \text{Dom}_a \cup \{U_i\}$ $H[i, C_i C'_i] \leftarrow Y_i \leftarrow \rho_a(U_i) \oplus C'_i; H[i, M_i M'_i] \leftarrow X_i \leftarrow Y_i \oplus U_i \oplus \rho_{a,i}(M'_i) \oplus M_i; V_i \leftarrow \rho_{a,i}(M'_i) \oplus M_i$ if $V_i \in \text{Dom}_a$ then bad \leftarrow true else $\text{Dom}_a \leftarrow \text{Dom}_a \cup \{V_i\}$ $X \leftarrow X \oplus X_i; Y \leftarrow Y \oplus Y_i$ if $M_u \neq \varepsilon$ then $X \leftarrow X \oplus \rho_u(\text{pad}(M_u)); Y \leftarrow Y \oplus \rho_u(\text{pad}(C_u))$ if $M_v \neq \varepsilon$ then $X \leftarrow X \oplus \rho_v(\text{pad}(M_v)); Y \leftarrow Y \oplus \rho_v(\text{pad}(C_v))$ $A \leftarrow \rho_x(M_y) \oplus X \oplus M_x; B \leftarrow \rho_y(C_y) \oplus Y \oplus C_x; S \leftarrow A \oplus B$ if $(A \in \text{Dom}_{xx}) \vee (B \in \text{Dom}_{yy})$ then bad \leftarrow true $\text{Dom}_{xx} \leftarrow \text{Dom}_{xx} \cup \{A\}; \text{Dom}_{yy} \leftarrow \text{Dom}_{yy} \cup \{B\}$ if $S \in \text{Set}$ then bad \leftarrow true else $\text{Set} \leftarrow \text{Set} \cup \{S\}$ // Constraints for ρ if bad and coll are not set // $\rho_{xx}(A) = M_y \oplus B; \rho_{yy}(B) = C_y \oplus A$ // $\rho_{aa,i}(S) = V_i \oplus Y_i$ for every $i = 1, \dots, m$ // $\rho_{vv}(S)[1.. M_v] = C_v \oplus M_v$ if $M_v \neq \varepsilon$ // $\rho_{uu}(S)[1.. M_u] = C_u \oplus M_u$ if $M_u \neq \varepsilon$ // $\rho_a(U_i) = Y_i \oplus C'_i$ if $\text{cmd} = \text{'enc'}$, and $\rho_a(V_i) = X_i \oplus M'_i$ otherwise, for every $i = 1, \dots, m$ </pre>
--

Fig. 11. Procedure VALIDATE to determine if ρ is valid. If ρ is indeed valid, the commented code dictates the constraints on ρ so that the real game results in the given transcript $(M^1, C^1, \text{cmd}_1), \dots, (M^q, C^q, \text{cmd}_q)$. Sets are initialized to \emptyset , and the flag **bad** is initialized to **false**. Function pad takes as input a string x with length $|x| \leq n$, and then returns x if $|x| = n$, and returns $x10^{n-|x|}$ otherwise.

it suffices to prove that

$$\Pr[\mathcal{A}^{G_2} \Rightarrow 0] - \Pr[\mathcal{A}^{H_2} \Rightarrow 0] \leq \frac{2\sigma^2 - \sigma q}{2^n} . \quad (2)$$

Since \mathcal{A} is deterministic, for any $i \geq 0$, the $(i+1)$ th query of \mathcal{A} is completely determined from the transcript $(M^1, C^1, cmd_1), \dots, (M^i, C^i, cmd_i)$ of the interaction between \mathcal{A} and the oracles up to the i th queries, and \mathcal{A} 's guess is uniquely determined from the full transcript $(M^1, C^1, cmd_1), \dots, (M^q, C^q, cmd_q)$, with each $cmd_j \in \{\text{'enc'}, \text{'dec'}\}$. Let \mathcal{S} be the set of all possible transcripts in game G_2 that makes \mathcal{A} output 0. For each $s \in \mathcal{S}$, let $\ell(s)$ be the total length of \mathcal{A} 's queries, according to s . In game G_2 the chance that s is produced is at least $2^{-\ell(s)}$, and thus

$$\sum_{s \in \mathcal{S}} 2^{-\ell(s)} \leq 1$$

because the left-hand side doesn't exceed the probability that \mathcal{A} outputs 0 in game G_2 . On the other hand, the chance that $s = (M^1, C^1, cmd_1), \dots, (M^q, C^q, cmd_q)$ is produced in game G_2 is at most

$$\prod_{i=0}^{q-1} \frac{1}{2^{|M^i|} - \sigma/2} \leq 2^{-\ell(s)} \prod_{i=0}^{q-1} \frac{1}{1 - \sigma/2^{2n+1}} \leq \frac{2^{-\ell(s)}}{1 - \sigma q/2^{2n+1}} \leq 2^{-\ell(s)} \cdot \left(1 + \frac{\sigma q}{2^{2n}}\right) \leq 2^{-\ell(s)} \cdot \left(1 + \frac{\sigma q}{2^n}\right),$$

where the second inequality is due to the fact that $(1 - x_1) \cdots (1 - x_q) \geq 1 - (x_1 + \cdots + x_q)$ for any $0 \leq x_1, \dots, x_q \leq 1$. We claim that for any $s \in \mathcal{S}$, the chance that s is produced in game H_2 is at least $2^{-\ell(s)}(1 - (2\sigma^2 - 2\sigma q)/2^n)$, and thus

$$\begin{aligned} \Pr[\mathcal{A}^{G_2} \Rightarrow 0] - \Pr[\mathcal{A}^{H_2} \Rightarrow 0] &\leq \sum_{s \in \mathcal{S}} 2^{-\ell(s)} \cdot \left(1 + \frac{\sigma q}{2^n}\right) - 2^{-\ell(s)} \left(1 - \frac{2\sigma^2 - 2\sigma q}{2^n}\right) \\ &\leq \sum_{s \in \mathcal{S}} 2^{-\ell(s)} \cdot \frac{2\sigma^2 - \sigma q}{2^n} \end{aligned}$$

establishing (2). To justify the claim above, consider an arbitrary transcript $s \in \mathcal{S}$. Let $s = (M^1, C^1, cmd_1), \dots, (M^q, C^q, cmd_q)$. We say that the function ρ is *valid* if it doesn't trigger the flag `bad` to true when we run $\text{VALIDATE}(M^1, C^1, cmd_1), \dots, \text{VALIDATE}(M^q, C^q, cmd_q)$, where the code of VALIDATE is specified in Fig. 11. If `bad` is not set then the commented code in VALIDATE specifies the constraints for ρ on tweaks $T \in \mathcal{T} \setminus \mathcal{T}_{\text{valid}}$, where $\mathcal{T}_{\text{valid}}$ is the set of tweaks T such that $\rho(T, \cdot)$ is used in running $\text{VALIDATE}(M^1, C^1, cmd_1), \dots, \text{VALIDATE}(M^q, C^q, cmd_q)$. If ρ is valid then the constraints never assign two different values to a point, and thus the conditional probability that ρ satisfies the prescribed constraints, given that ρ is valid, is at least $2^{-\ell(s)}$. What remains is to prove that the probability that `bad` is set is at most $(2\sigma^2 - 2\sigma q)/2^n$.

CODE INTERPRETATION. In the code, we maintain a map $H : \mathbb{N} \times \{0, 1\}^n \rightarrow \{0, 1\}^n$ such that $H[i, M_i M'_i] \leftarrow X_i$ and $H[i, C_i C'_i] \leftarrow Y_i$. Wlog, consider the case $cmd = \text{'enc'}$. First, the assignment $H[i, M_i M'_i] \leftarrow X_i$ doesn't overwrite an existing point in H , because if there is a prior query $(\tilde{M}, \tilde{C}, \widetilde{cmd})$ such that $\tilde{M}_i \tilde{M}'_i = M_i M'_i$ then $X_i = \tilde{X}_i$, and if there is a prior query $(\tilde{M}, \tilde{C}, \widetilde{cmd})$ such that $\tilde{C}_i \tilde{C}'_i = M_i M'_i$ then $X_i = \tilde{Y}_i$. When we run the assignment $H[i, M_i M'_i] \leftarrow X_i \leftarrow \rho_a(V_i) \oplus M'_i$, if `bad` is not set and $H[i, M_i M'_i] = \perp$ then ρ_a has never been evaluated on V_i , and thus X_i is a fresh random string. Next, the assignment $H[i, C_i C'_i] \leftarrow Y_i$ doesn't overwrite an existing point in H , as $C'_i \neq M'_i$ and $C'_i \neq \tilde{C}'_i$ for any prior query $(\tilde{M}, \tilde{C}, \widetilde{cmd})$. Moreover, when we run the assignment $H[i, C_i C'_i] \leftarrow Y_i \leftarrow X_i \oplus V_i + \rho_{a,i}(C'_i) \oplus C_i$, as $\rho_{a,i}$ has never been evaluated on C'_i , the

string Y_i is a fresh random string. In other words, H is a random oracle, and $X_i \leftarrow H[i, M_i M'_i]$ and $Y_i \leftarrow H[i, C_i C'_i]$ for any query (M, C) and any $i \leq \lfloor |M|/2n \rfloor - 2$.

A TECHNICAL LEMMA . We show that for any two queries (M, C, cmd) and $(\tilde{M}, \tilde{C}, \widetilde{cmd})$, it's unlikely that $X \oplus M_x = \tilde{X} \oplus \tilde{M}_x$, unless $M[1..|M| - n] = \tilde{M}[1..|\tilde{M}| - n]$. By symmetry, it's unlikely that $Y \oplus C_x = \tilde{Y} \oplus \tilde{C}_x$, unless $C[1..|C| - n] = \tilde{C}[1..|\tilde{C}| - n]$.

Lemma 1. For any two queries (M, C, cmd) and $(\tilde{M}, \tilde{C}, \widetilde{cmd})$, (a) if $M[1..|M| - n] \neq \tilde{M}[1..|\tilde{M}| - n]$ then $\Pr[X \oplus M_x = \tilde{X} \oplus \tilde{M}_x] \leq 2^{-n}$, and (b) if $C[1..|C| - n] \neq \tilde{C}[1..|\tilde{C}| - n]$ then $\Pr[Y \oplus C_x = \tilde{Y} \oplus \tilde{C}_x] \leq 2^{-n}$.

Proof. We'll give a proof for part (a); part (b) follows due to symmetry. If $M[1..|M| - 2n] = \tilde{M}[1..|\tilde{M}| - 2n]$ then $M_x \neq \tilde{M}_x$ and $X = \tilde{X}$. Hence $X \oplus M_x \neq \tilde{X} \oplus \tilde{M}_x$. Consider the case that $M[1..|M| - 2n] \neq \tilde{M}[1..|\tilde{M}| - 2n]$. Let $m = \lfloor |M|/2n \rfloor - 2$ and $m' = \lfloor |\tilde{M}|/2n \rfloor - 2$. Wlog, assume that $m \geq m'$. We consider the following cases.

CASE 1: $m > m'$. Then X_m is independent of \tilde{X} , and thus the chance that $X \oplus M_x = \tilde{X} \oplus \tilde{M}_x$ is at most 2^{-n} .

CASE 2: $m = m'$ and there is an index $i \leq m$ such that $M_i M'_i \neq \tilde{M}_i \tilde{M}'_i$, and thus X_i and \tilde{X}_i are independent. Then $X \oplus M'_0 = \tilde{X} \oplus \tilde{M}'_0$ with probability at most 2^{-n} .

CASE 3: $m = m'$ and $M_i M'_i = \tilde{M}_i \tilde{M}'_i$ for every $i \leq m$. If $M_u \neq \tilde{M}_u$ then one of them must be nonempty; wlog, suppose that $M_u \neq \varepsilon$. Then $X_u = \rho_u(M_u)$ is independent of \tilde{X} , and $X \oplus M_x = \tilde{X} \oplus \tilde{M}_x$ with probability at most 2^{-n} . So suppose that $M_u = \tilde{M}_u$. Then $M_v \neq \tilde{M}_v$, and thus one of them must be nonempty; wlog assume that $M_v \neq \varepsilon$. Then $X_v = \rho_v(M_v 10^*)$ is independent of \tilde{X} , and $X \oplus M_x = \tilde{X} \oplus \tilde{M}_x$ with conditional probability at most 2^{-n} . \square

ACCOUNTING FOR BAD EVENTS. The flag **bad** is set only if one of the following happens:

- There are some (M, C, cmd) and $(\tilde{M}, \tilde{C}, \widetilde{cmd})$ such that (1) $M[1..|M| - n] \neq \tilde{M}[1..|\tilde{M}| - n]$, but (2) $X \oplus M_x = \tilde{X} \oplus \tilde{M}_x$. From Lemma 1, this happens with conditional probability at most $q^2/2^{n+1}$.
- There are some (possibly the same) queries (M, C, cmd) and $(\tilde{M}, \tilde{C}, \widetilde{cmd})$ and $i, j \geq 1$ and such that (1) either $i \neq j$ or $M_i M'_i \neq \tilde{M}_j \tilde{M}'_j$ but (2) $\rho_{a,i}(M'_i) \oplus M_i = \rho_{a,j}(\tilde{M}'_j) \oplus \tilde{M}_j$. Summing over for at most $\sigma - 2q$ pairs $M_i M'_i$ and $\tilde{M}_j \tilde{M}'_j$, this event happens with probability at most $(\sigma - 2q)^2/2^{n+1}$.
- There are some (M, C, cmd) and $(\tilde{M}, \tilde{C}, \widetilde{cmd})$ such that (1) $X \oplus M_x \neq \tilde{X} \oplus \tilde{M}_x$, but (2) $\rho_x(M_y) \oplus X \oplus M_x = \rho_x(\tilde{M}_y) \oplus \tilde{X} \oplus \tilde{M}_x$. This event happens with probability at most $q^2/2^{n+1}$.
- The dual of the bad events above, where M_i becomes C_i , X becomes Y , and so on. This happens with probability at most $(2q^2 + (\sigma - q)^2)/2^{n+1}$.
- There are some (possibly the same) queries (M, C, cmd) and $(\tilde{M}, \tilde{C}, \widetilde{cmd})$ and $i, j \geq 1$ and such that (1) either $i \neq j$ or $M_i M'_i \neq \tilde{C}_j \tilde{C}'_j$ but (2) $\rho_{a,i}(M'_i) \oplus M_i = \rho_{a,j}(\tilde{C}'_j) \oplus \tilde{C}_j$. Summing over for at most $\sigma - 2q$ strings $M_i M'_i$ at most $\sigma - 2q$ strings $\tilde{C}_j \tilde{C}'_j$, this event happens with probability at most $(\sigma - 2q)^2/2^n$.

- There is a query (M, C, cmd) and a prior query $(\tilde{M}, \tilde{C}, \widetilde{cmd})$ such that $S = \tilde{S}$. As $S = \rho_x(M_y) \oplus M_x \oplus X \oplus \rho_y(C_y) \oplus C_x \oplus Y$, $\tilde{S} = \rho_x(\tilde{M}_y) \oplus \tilde{M}_x \oplus \tilde{X} \oplus \rho_y(\tilde{C}_y) \oplus \tilde{C}_x \oplus \tilde{Y}$, and either $C_y \notin \{M_y, \tilde{M}_y, \tilde{C}_y\}$ or $M_y \notin \{C_y, \tilde{M}_y, \tilde{C}_y\}$, this happens with probability at most $q^2/2^{n+1}$.

Summing up, the chance that **bad** is set is at most

$$\frac{2.5q^2 + 2(\sigma - 2q)^2}{2^n} = \frac{2\sigma^2 - 8\sigma q + 10.5q^2}{2^n} \leq \frac{2\sigma^2 - 2\sigma q}{2^n};$$

the last inequality is due to the fact that $\sigma \geq 2q$.

B.5 Proof of Theorem 5

The reduction \mathcal{R} creates from \mathcal{A} the adversary \mathcal{B} as follows. It runs \mathcal{A} . Each time the latter makes an **Enc** query, the former runs the encryption procedure of $\text{AEZ}[\tilde{E}]$, but each $\tilde{E}_K^T(X)$ is replaced by querying (T, X) to the oracle of \mathcal{B} . Likewise, for each **Dec** query of \mathcal{A} , adversary \mathcal{B} runs the decryption procedure of $\text{AEZ}[\tilde{E}]$, but each $\tilde{E}_K^T(X)$ is replaced by querying (T, X) to the oracle of \mathcal{B} . Finally, \mathcal{B} outputs the same guess as \mathcal{A} .

Let $\text{AEZ}[\text{Perm}(\mathcal{T}_{\text{aez}}, 128)]$ be the ideal variant of $\text{AEZ}[\tilde{E}]$ where \tilde{E} is replaced by an ideal TBC $\tilde{\pi} : \mathcal{T}_{\text{aez}} \times \{0, 1\}^{128} \rightarrow \{0, 1\}^{128}$. Let S be the simulator in Theorem 3. It suffices to show that

$$\mathbf{Adv}_{\text{AEZ}[\text{Perm}(\mathcal{T}_{\text{aez}}, 128)], S}^{\text{rae}}(\mathcal{A}) \leq \frac{3s^2}{2^{128}}. \quad (3)$$

Let H be the ideal variant of AEZ-hash in which E is replaced by $\tilde{\pi}$. Note that s is the sum of the number of processed blocks from two sources: AEZ-core, and AEZ-prf; let these numbers be σ and t respectively. Equation (3) is obtained via the following results:

- Theorem 3 in Section 5 to justify the RAE security from the EtE construction,
- Theorem 4 in Section 6 to justify that AEZ-core is a secure length-preserving strong tweakable-PRP on $\text{BYTE}^{\geq 32}$, contributing $2\sigma^2/2^{128}$ to the total advantage,
- Theorem 7 in Appendix C for tweaking AEZ-core. This part contributes at most $\frac{(\sigma/4)^2}{2^{128}} + \mathbf{Adv}_H^{\text{axu}}(\sigma) \leq \frac{0.1\sigma^2}{2^{128}} + \mathbf{Adv}_H^{\text{axu}}(\sigma)$ to the total advantage.

What remains is to bound (i) the AXU advantage of H , (ii) the PRF-advantage of the ideal variant of AEZ-prf and (iii) the advantage in distinguishing AEZ-core on $\tilde{\pi}$ and AEZ-core on an ideal random function $f : \mathcal{T}_{\text{aez}} \times \{0, 1\}^{128} \rightarrow \{0, 1\}^{128}$. For (i), note that $\text{Coll}_H(m, m') \leq 1/(2^{128} - 1)$ for every $m, m' \in \mathbb{N}$, and thus

$$\mathbf{Adv}_H^{\text{axu}}(z) \leq \frac{0.5z(z-1)}{2^{128}-1} \leq \frac{0.5z^2}{2^{128}}$$

for any $z \in \{0, \dots, 2^{128}\}$. For (ii), the PRF advantage of the ideal variant of AEZ-prf is at most $t^2/2^{128}$. For (iii), note that \mathcal{A} 's queries results in calling $\tilde{\pi}^{(0,0)}$ at most σ times. Suppose that \mathcal{A} 's queries result in calling $\tilde{\pi}$ on tweaks $T_1, \dots, T_m \neq (0, 0)$ with q_1, \dots, q_m queries respectively. Note that $q_1, \dots, q_m \leq \sigma/2$ and $q_1 + \dots + q_m \leq 1.5\sigma$. By PRP/PRF Switching Lemma [31], the advantage in distinguishing $\tilde{\pi}$ and f on tweaks T_1, \dots, T_m with q_1, \dots, q_m queries respectively, and on tweak $(0, 0)$ with σ queries, is at most

$$\frac{\sigma^2}{2 \cdot 2^{128}} + \sum_{i=1}^m \frac{q_i^2}{2 \cdot 2^{128}} \leq \frac{\sigma^2}{2 \cdot 2^{128}} + \sum_{i=1}^m \frac{q_i \sigma}{4 \cdot 2^{128}} \leq \frac{0.9\sigma^2}{2^{128}}.$$

Summing up,

$$\mathbf{Adv}_{\text{AEZ}[\text{Perm}(\mathcal{T}_{\text{aez},128})],S}^{\text{rae}}(\mathcal{A}) \leq \frac{3.5\sigma^2 + t^2}{2^{128}} \leq \frac{3.5s^2}{2^{128}}$$

as claimed.

B.6 Proof of Theorem 6

Let q be the number of calls to E . Then $q \leq 2.5s - 2$. Let $\pi : \{0,1\}^{128} \rightarrow \{0,1\}^{128}$ be an ideal random permutation, and let $\tilde{\pi}^{i,j}(X) = \pi(X \oplus (i+1)I \oplus jJ)$ where $I = \pi(\mathbf{0})$ and $J = \pi(\mathbf{1})$ for every $(i,j) \in \mathcal{T}_{\text{aez}}$. From Theorem 5, what remains is to show that, $\mathbf{Adv}_{\tilde{\pi}}^{\text{prp}}(\mathcal{D}) \leq 1.5(q+2)^2/2^{128}$ for any adversary \mathcal{D} that makes at most q queries, which is implied by [49, Theorem 7]. (The theorem statement of [49, Theorem 7] states that $\mathbf{Adv}_{\tilde{\pi}}^{\text{prp}}(\mathcal{D}) \leq 4.5q^2/2^{128}$, but in our setting, the proof of [49, Theorem 7] actually yields $\mathbf{Adv}_{\tilde{\pi}}^{\text{prp}}(\mathcal{D}) \leq 0.5q^2/2^{128} + (q+2)^2/2^{128}$ and then upperbounds $q+2 \leq 2q$.)

C Tweaking a Wide-Block Blockcipher

In Section 5 we have shown that RAE can be achieved from the EtE construction using a an arbitrary-input blockcipher with tweak space $\mathcal{T} = \Sigma^* \times \Sigma^* \times \mathbb{N}$. In AEZ, we consider $\Sigma = \text{BYTE}$ and then build an arbitrary-input blockcipher but without the tweaks, which is AEZ-core for messages at least 32 bytes, and AEZ-tiny for shorter messages. We now show how to tweak this generalized blockcipher. We'll use the XEX processing [35, 49] to tweak AEZ-core. Recall that AEZ-tiny is a Feistel network whose round functions are derived from a TBC $E : \mathcal{T}' \times \{0,1\}^{128} \rightarrow \{0,1\}^{128}$. To tweak AEZ-tiny, we'll expand the tweak space of E to $\mathcal{T} \times \mathcal{T}'$ via the XE processing [35, 49]. (Since there's no query to E_K^{-1} , we don't need XEX processing.) In both cases, we'll hash the tweak $T \in \mathcal{T}$ via an almost-xor universal (AXU) hash. To save the context size, AEZ-tiny and AEZ-core will use the same key for the AXU hash. To justify this sharing, we'll extend the $\pm\text{prp}$ security as follows. The tweak space \mathcal{T} is partitioned into two sets \mathcal{T}^\pm and \mathcal{T}^+ . The adversary can only make decryption queries for tweaks $T \in \mathcal{T}^\pm$. This definition, put forward by Krovetz and Rogaway [34], aims at minimizing the overhead of tweaking a blockcipher. Below, we'll extend the classic notion of AXU hash for a possibly infinite message space.

AXU HASH. Let $n \geq 1$ be an integer and let $H : \mathcal{K} \times \mathcal{U} \rightarrow \{0,1\}^n$. For our application, each $U \in \mathcal{U}$ will be a vector whose components are string vectors. We write $\|U\|$ to denote the length of the string encoding of U . For each $m, m' \in \mathbb{N}$, define $\text{Coll}_H(m, m')$ as the maximum, taken over all $y \in \{0,1\}^n$ and distinct $U, U' \in \mathcal{U}$ such that $\lceil \|U\|/n \rceil = m$ and $\lceil \|U'\|/n \rceil = m'$, of $\Pr[K \leftarrow \mathcal{K} : H_K(U) \oplus H_K(U') = y]$. If there are no such U and U' then $\text{Coll}_H(m, m') = 0$. For each $s \in \mathbb{N}$, let

$$\mathbf{Adv}_H^{\text{axu}}(s) = \max_{\substack{q, m_1, \dots, m_q \\ m_1 + \dots + m_q = s}} \left\{ \sum_{1 \leq i < j \leq q} \text{Coll}_H(m_i, m_j) \right\}$$

EXPANDING THE TWEAK SPACE. Let $n \geq 1$ be an integer and $\mathcal{M} \subseteq \{0,1\}^*$ be a set such that (i) $|x| \geq n$ for every $x \in \mathcal{M}$, and (ii) if $x \in \mathcal{M}$ then $\{0,1\}^{|x|} \subseteq \mathcal{M}$. Suppose that we have an

AXU hash $H: \mathcal{K} \times \mathcal{U} \rightarrow \{0, 1\}^n$ and a tweakable blockcipher $\tilde{\mathbb{E}}: \mathcal{K}' \times \mathcal{V} \times \mathcal{M} \rightarrow \mathcal{M}$, where \mathcal{V} is partitioned to \mathcal{V}^\pm and \mathcal{V}^+ . Consider the following way $\text{XT}[H, \tilde{\mathbb{E}}]$ to build a tweakable blockcipher $\tilde{\mathbb{E}}: (\mathcal{K} \times \mathcal{K}') \times \mathcal{T} \times \mathcal{M} \rightarrow \mathcal{M}$, with $\mathcal{T} = \mathcal{U} \times \mathcal{V}$ and $\mathcal{T}^\pm = \mathcal{U} \times \mathcal{V}^\pm$ and $\mathcal{T}^+ = \mathcal{U} \times \mathcal{V}^+$. On input M and tweak $T = (U, V)$, let $S = 0^m \parallel H_K(U) \parallel 0^{|M|-m-n}$, where $m = \max\{0, |M| - 2n\}$. If $T \in \mathcal{T}^\pm$ then $\tilde{\mathbb{E}}_{K, K'}^T(M) = S \oplus \tilde{\mathbb{E}}_{K'}^V(M \oplus S)$, otherwise $\tilde{\mathbb{E}}_{K, K'}^T(M) = \tilde{\mathbb{E}}_{K'}^V(M \oplus S)$. The following says that $\tilde{\mathbb{E}}$ achieves the extended $\pm\text{prp}$ security. This result is close to one of Liskov, Rivest, and Wagner [35].

We can justify the key sharing of AEZ-tiny and AEZ-core by applying Theorem 7 for $n = 128$, $\mathcal{M} = \text{BYTE}^{16} \cup \text{BYTE}^{\geq 32}$, $\mathcal{V}^+ = \{0\} \times \mathcal{N} \times \mathcal{A}$, $\mathcal{V}^\pm = \{(1, 0)\}$, $\tilde{\mathbb{E}}_K^{(1,0)}$ as AEZ-core, and $\tilde{\mathbb{E}}_K^{(0,T)}$ as the TBC implementing the round functions of AEZ-tiny with tweak T .

Theorem 7. Let $\tilde{\mathbb{E}}: \mathcal{K} \times \mathcal{M} \rightarrow \mathcal{M}$ be a tweakable blockcipher and $H: \mathcal{K}' \times \mathcal{T} \rightarrow \{0, 1\}^n$ be an AXU hash. There is an explicitly given reduction \mathcal{R} with the following property. For any adversary \mathcal{A} , adversaries $\mathcal{B} = \mathcal{R}(\mathcal{A})$ satisfies

$$\mathbf{Adv}_{\text{XT}[H, \tilde{\mathbb{E}}]}^{\pm\text{prp}}(\mathcal{A}) \leq q^2/2^n + \mathbf{Adv}_{\tilde{\mathbb{E}}}^{\pm\text{prp}}(\mathcal{B}) + \mathbf{Adv}_H^{\text{axu}}(s),$$

where s is the total block length of the string encodings of the tweaks in \mathcal{A} 's queries and q is the number of \mathcal{A} 's queries. Adversary \mathcal{B} has about the same running time as \mathcal{A} plus the time using H to process the tweaks in \mathcal{A} 's queries. It makes q queries as \mathcal{A} , and the total block length of its queries is the same as that of \mathcal{A} .

Proof. The reduction \mathcal{R} creates from \mathcal{A} the adversary \mathcal{B} as follows. It samples $K_1 \leftarrow \mathcal{K}_1$ and runs \mathcal{A} . For each encryption query (T, M) of \mathcal{A} , with $T = (U, V)$, adversary \mathcal{B} computes $S \leftarrow 0^m \parallel H_K(U) \parallel 0^{|M|-m-n}$, where $m = \max\{0, |M| - 2n\}$, and queries $(V, M \oplus S)$ to its left oracle to gets answer C . It returns $C \oplus S$ to \mathcal{A} if $T \in \mathcal{T}^\pm$, and returns C to \mathcal{A} otherwise. For each decryption query (T, C) of \mathcal{A} , with $T = (U, V)$, adversary \mathcal{B} computes $S \leftarrow 0^m \parallel H_K(U) \parallel 0^{|C|-m-n}$, where $m = \max\{0, |C| - 2n\}$, and queries $(V, C \oplus S)$ to its right oracle to gets answer M , and returns $M \oplus S$ to \mathcal{A} . Finally, it outputs the same guess as \mathcal{A} .

Let $\text{Perm}(\mathcal{V}, \mathcal{M})$ denote the set of all functions $f: \mathcal{V} \times \mathcal{M} \rightarrow \mathcal{M}$ such that each $f(V, \cdot)$ is a length-preserving permutation on \mathcal{M} , for every $V \in \mathcal{V}$. Let $\text{XT}[H, \text{Perm}(\mathcal{V}, \mathcal{M})]$ denote the variant of $\text{XT}[H, \mathbb{E}]$ in which $\mathbb{E}_{K'}$ is replaced by an ideal $\tilde{\pi} \leftarrow \text{Perm}(\mathcal{V}, \mathcal{M})$. It suffices to show that

$$\mathbf{Adv}_{\text{XT}[H, \text{Perm}(\mathcal{V}, \mathcal{M})]}^{\pm\text{prp}}(\mathcal{A}) \leq q^2/2^n + \mathbf{Adv}_H^{\text{axu}}(s) .$$

Consider games G_1 – G_6 in Fig. 12. In each game, adversary \mathcal{A} interrogates oracle ENC for encryption queries, and oracle DEC for decryption queries. Without loss of generality, assume that the adversary doesn't make redundant queries, that is, (i) it doesn't repeat prior queries for each oracle, (ii) once it queries (T, M) to ENC to get C , it won't query (T, C) to DEC, and (iii) once it queries (T, C) to DEC to get M , it won't query (T, M) to ENC. Game G_1 corresponds to the real setting and game G_6 to the random setting.

We explain the game chain to the terminal one. Let $\text{Func}(\mathcal{V}, \mathcal{M})$ be the set of functions $f: \mathcal{V} \times \mathcal{M} \rightarrow \mathcal{M}$ such that each $f(V, \cdot)$ is length-preserving, for every $V \in \mathcal{V}$. Game G_2 is identical to G_1 , except that instead of using an ideal $\tilde{\pi} \leftarrow \text{Perm}(\mathcal{V}, \mathcal{M})$ we'll use an ideal $f \leftarrow \text{Func}(\mathcal{V}, \mathcal{M})$. Suppose that \mathcal{A} uses ℓ tweaks T_1, \dots, T_ℓ , and makes q_i queries for tweak T_i . Games G_1 and G_2 are identical-until-bad, and thus

$$\Pr[\mathcal{A}^{G_1} \Rightarrow 1] - \Pr[\mathcal{A}^{G_2} \Rightarrow 1] \leq \Pr[\mathcal{A}^{G_2} \text{ sets bad}] \leq \sum_{i=1}^{\ell} \frac{q_i^2}{2^{n+1}} \leq \frac{q^2}{2^{n+1}} .$$

<pre> proc ENC(T, M) $(U, V) \leftarrow T$; $m \leftarrow \max\{0, M - 2n\}$ $S \leftarrow 0^m \parallel H_K(U) \parallel 0^{ M -m-n}$ $x \leftarrow M \oplus S$; $y \leftarrow \{0, 1\}^{ M }$ if $T \in \mathcal{T}^\pm$ then $\text{Mask} \leftarrow S$ else $\text{Mask} \leftarrow 0^{ M }$ if $x \in \text{Dom}(V)$ then $y \leftarrow P[V, x]$; return $y \oplus \text{Mask}$ if $y \in \text{Ran}(V)$ then $\text{bad} \leftarrow \text{true}$; $y \leftarrow \{0, 1\}^{ M } \setminus \text{Ran}(V)$ $P[V, x] \leftarrow y$; $\text{Dom}(V) \leftarrow \text{Dom}(V) \cup \{x\}$ $R[V, y] \leftarrow x$; $\text{Ran}(V) \leftarrow \text{Ran}(V) \cup \{y\}$ return $y \oplus \text{Mask}$ </pre>	<pre> proc DEC(T, C) Games $\boxed{G_1} / G_2$ $(U, V) \leftarrow T$; $m \leftarrow \max\{0, C - 2n\}$ $S \leftarrow 0^m \parallel H_K(U) \parallel 0^{ C -m-n}$ $y \leftarrow C \oplus S$; $x \leftarrow \{0, 1\}^{ C }$ if $y \in \text{Ran}(V)$ then $(x \leftarrow R[V, y]$; return $x \oplus S)$ if $x \in \text{Dom}(V)$ then $\text{bad} \leftarrow \text{true}$; $x \leftarrow \{0, 1\}^{ C } \setminus \text{Dom}(V)$ $P[V, x] \leftarrow y$; $\text{Dom}(V) \leftarrow \text{Dom}(V) \cup \{x\}$ $R[V, y] \leftarrow x$; $\text{Ran}(V) \leftarrow \text{Ran}(V) \cup \{y\}$ $M \leftarrow x \oplus S$; return M </pre>
<pre> proc ENC(T, M) $(U, V) \leftarrow T$; $m \leftarrow \max\{0, M - 2n\}$ $S \leftarrow 0^m \parallel H_K(U) \parallel 0^{ M -m-n}$ $x \leftarrow M \oplus S$; $C \leftarrow \{0, 1\}^{ M }$ if $T \in \mathcal{T}^\pm$ then $\text{Mask} \leftarrow S$ else $\text{Mask} \leftarrow 0^{ M }$ if $x \in \text{Dom}(V)$ then $\text{bad} \leftarrow \text{true}$; $C \leftarrow P[V, x] \oplus \text{Mask}$ $y \leftarrow C \oplus \text{Mask}$; $P[V, x] \leftarrow y$ $\text{Dom}(V) \leftarrow \text{Dom}(V) \cup \{x\}$ $R[V, y] \leftarrow x$; $\text{Ran}(V) \leftarrow \text{Ran}(V) \cup \{y\}$ return C </pre>	<pre> proc DEC(T, C) Games $\boxed{G_3} / G_4$ $(U, V) \leftarrow T$; $m \leftarrow \max\{0, C - 2n\}$ $S \leftarrow 0^m \parallel H_K(U) \parallel 0^{ C -m-n}$ $y \leftarrow C \oplus S$; $M \leftarrow \{0, 1\}^{ C }$ if $y \in \text{Ran}(V)$ then $\text{bad} \leftarrow \text{true}$; $M \leftarrow R[V, y] \oplus S$ $x \leftarrow M \oplus S$; $P[V, x] \leftarrow y$; $\text{Dom}(V) \leftarrow \text{Dom}(V) \cup \{x\}$ $R[V, y] \leftarrow x$; $\text{Ran}(V) \leftarrow \text{Ran}(V) \cup \{y\}$ return M </pre>
<pre> proc ENC(T, M) $(U, V) \leftarrow T$; $C \leftarrow \{0, 1\}^{ M }$ if $C \in \text{Ran}(V)$ then $\text{bad} \leftarrow \text{true}$; $C \leftarrow \{0, 1\}^{ M } \setminus \text{Ran}(V)$ $\text{Dom}(V) \leftarrow \text{Dom}(V) \cup \{M\}$ $\text{Ran}(V) \leftarrow \text{Ran}(V) \cup \{C\}$ return C </pre>	<pre> proc DEC(T, C) Games $G_5 / \boxed{G_6}$ $(U, V) \leftarrow T$; $M \leftarrow \{0, 1\}^{ C }$ if $M \in \text{Dom}(V)$ then $\text{bad} \leftarrow \text{true}$; $M \leftarrow \{0, 1\}^{ C } \setminus \text{Dom}(V)$ $\text{Dom}(V) \leftarrow \text{Dom}(V) \cup \{M\}$; $\text{Ran}(V) \leftarrow \text{Ran}(V) \cup \{C\}$ return M </pre>

Fig. 12. Games G_1 – G_6 in the proof of Theorem 7. Games G_1, G_3, G_6 include the corresponding boxed statements, but games G_2, G_4, G_5 do not. In each game, there is an implicit procedure INITIALIZE that samples $K_1 \leftarrow \mathcal{K}_1$. Sets are initialized to \emptyset . Every entry of all arrays is initialized to \perp .

In game G_3 , instead of sampling y at random and computing C as $y \oplus \text{Mask}$, we sample C at random at let $y \leftarrow C \oplus \text{Mask}$. The change is conservative. In game G_4 , both ENC and DEC always return a fresh random answer. Games G_3 and G_4 are identical-until-bad, and thus

$$\Pr[\mathcal{A}^{G_3} \Rightarrow 1] - \Pr[\mathcal{A}^{G_4} \Rightarrow 1] \leq \Pr[\mathcal{A}^{G_4} \text{ sets bad}] .$$

We now bound the chance that G_4 sets **bad**. Without loss of generality, we can assume that the adversary is non-adaptive, because the answers from the oracles are always independent, uniformly random strings. Game G_4 sets **bad** only if the adversary can find distinct (U, M) and (U', M') such that $|M| = |M'|$ and

$$(0^m \parallel H_K(U) \parallel 0^{|M|-n-m}) \oplus M = (0^m \parallel H_K(U') \parallel 0^{|M'|-m-n}) \oplus M', \quad (4)$$

where $m = \max\{0, |M| - 2n\}$. If $U = U'$ then $M \neq M'$ because $(U, M) \neq (U', M')$, and thus Equation (4) won't happen. If $U \neq U'$ then Equation (4) happens with probability at most

$\text{Coll}(\lceil \|U\|/n \rceil, \lceil \|U'\|/n \rceil)$. Hence $\Pr[\mathcal{A}^{G_4} \text{ sets bad}] \leq \mathbf{Adv}_H^{\text{axu}}(s)$. Next, game G_5 is the simplified version of game G_4 . Game G_6 is identical to G_5 , except that we maintain the consistency among the queries. Then

$$\Pr[\mathcal{A}^{G_5} \Rightarrow 1] - \Pr[\mathcal{A}^{G_6} \Rightarrow 1] \leq \Pr[\mathcal{A}^{G_5} \text{ sets bad}] \leq \sum_{i=1}^{\ell} \frac{q_i^2}{2^{n+1}} \leq \frac{q^2}{2^{n+1}} .$$

Summing up, $\mathbf{Adv}_{\text{XT}[H, \text{Perm}(\mathcal{V}, \mathcal{M})]}^{\pm \widetilde{\text{prp}}}(\mathcal{A}) \leq \Pr[\mathcal{A}^{G_1} \Rightarrow 1] - \Pr[\mathcal{A}^{G_6} \Rightarrow 1] \leq q^2/2^n + \mathbf{Adv}_H^{\text{axu}}(s)$. \square

D An Insecure Variant of AEZ-core

Numerous variants of AEZ-core were considered to arrive at AEZ-core. Most simplifications of the final version do not work. As an example, consider trying to cheapen the design by using $c_i \cdot f_{\text{aa},1}(S)$ instead of $f_{\text{aa},i}(S)$ to whiten the middle of each Feistel network, where each c_i is a public constant, and the dot is the multiplication in $\text{GF}(2^n)$. For example, one might hope this works for $c_i = 1$ or $c_i = i$. But this modification is insecure for any choice of c_i values.

For each $L \subseteq \{1, \dots, n+1\}$ let $\theta(L) = \bigoplus_{i \in L} c_i$. Let $D \neq \emptyset$ be a subset of $\{1, \dots, n+1\}$ such that $\theta(D) = 0^n$. Such a set D must exist. Assume to the contrary that $\theta(L) \neq 0^n$ for all nonempty $L \subseteq \{1, \dots, n+1\}$. Then for any distinct nonempty subsets $L, L' \subseteq \{1, \dots, n+1\}$, we have $\theta(L) \neq \theta(L')$. This means that for $2^{n+1} - 1$ nonempty subsets $L \subseteq \{1, \dots, n+1\}$ we have $2^{n+1} - 1 > 2^n$ corresponding distinct elements $\theta(L)$ of $\text{GF}(2^n)$, which is a contradiction.

We now describe an attack to the modified AEZ-core. Our attack only uses strings of length $\ell = 2n(n+3)$. Let M and \tilde{M} be arbitrary distinct ℓ -bit strings such that they agree everywhere except the last two blocks. Query M and \tilde{M} to the first oracle to get answers C and \tilde{C} respectively. In the real game, we'll have $X_i = \tilde{X}_i$ and $\tilde{Y}_i = Y_i \oplus (c_i \cdot (S \oplus \tilde{S}))$ for every $1 \leq i \leq n+2$. Next, let C^* be the “mixed” ciphertext such that, for every $1 \leq i \leq n+3$, the $(2i-1)$ 'th and $2i$ 'th blocks of C^* are the same as those of \tilde{C} if $i \in D$, otherwise C^* would borrow the corresponding two blocks of C . Query C^* to the second oracle to get an answer M^* . Let $\bar{D} = \{1, \dots, n+2\} \setminus D$. In the real game, the query C^* will generate $Y_i^* = \tilde{Y}_i$ for every $i \in D$, and $Y_i^* = Y_i$ for every $i \in \bar{D}$. Then

$$Y^* = \bigoplus_{i \in D} \tilde{Y}_i \oplus \bigoplus_{j \in \bar{D}} Y_j = Y \oplus \bigoplus_{i \in D} ((S \oplus \tilde{S}) \cdot c_i) = Y .$$

Consequently, $S^* = S$ and thus M^* and M agree at the $(2n+3)$ th and $(2n+4)$ th blocks. The latter event happens with probability at most 2^{-n} in the random game. Hence this attack wins with advantage at least $1 - 2^{-n}$.