Beetle Family of Lightweight and Secure Authenticated Encryption Ciphers

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2 Motivation

3 Specification for Beetle

4 Hardware Implementation Results of Beetle

5 Conclusions

Authenticated Encryption (AE)

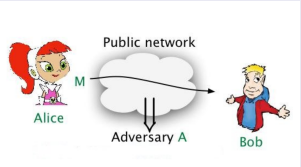

Figure: Data Transmission

- A symmetric encryption scheme $\mathcal{AE} = (\mathcal{K}, \mathcal{E}, \mathcal{D})$
- $\mathcal{E} : \mathcal{K} \times \mathcal{M} \times \mathcal{N} \times \mathcal{A} \rightarrow \mathcal{C}$
- $\mathcal{D} : \mathcal{K} \times \mathcal{C} \times \mathcal{N} \times \mathcal{A} \rightarrow \mathcal{M} \cup \{\perp\}$
- $\mathcal{C} \leftarrow$ set of *tagged* ciphertexts $((C, T)$ pair$)$
- $\perp$: special symbol to denote reject

Authenticated Encryption (AE)

Nonce

- Arbitrary number used only once for each encryption
- Useful as initialization vectors. Example: Counter

Associated Data

- Header of the Message (not encrypted but authenticated)
- Example: IP Address

Authenticated Encryption (AE)

Why AE?

In practice both privacy and authenticity are desirable

A doctor wishes to send medical information about Alice to the medical database. Then

- We want data privacy to ensure Alice's medical records remain confidential
- We want integrity to ensure the person sending the information is really the doctor and the information was not modified in transit

We refer to this as authenticated encryption

Security of Authenticated Encryption

Privacy

We want IND-CPA

Integrity

- Adversary's goal: Receiver accepts a forged tuple $((C^*, T^*), N^*, A^*)$
- INT-CTXT: Any forged tuple is rejected with high probability

Goal - IND-CPA + INT-CTXT

Unified AE Security (Random permutation Model)

- Adversary $\mathcal{A}$ runs in time t
- $\mathcal{A}$ makes q_e enc queries (σ_e enc blocks)
- q_f offline permutation queries to f or f^{-1} (simply $f^{\pm}$)
- q_d forge queries (σ_d forge blocks)

- $\mathbf{Adv}^{\mathrm{AE}}_{\mathcal{E}}(\mathcal{A}) = \Delta_{\mathcal{A}}((f^{\pm}, \mathcal{E}_K, \mathcal{D}_K); (f^{\pm}, \$, \perp))$
- $\$$ returns a random string from the range set of $\mathcal{E}_K$
- $\perp$ oracle always returns $\perp$ (*reject* always)

- $\mathbf{Adv}^{\mathrm{AE}}_{\mathcal{E}}((q_e, q_f, q_d), (\sigma_e, \sigma_d), t) = \max_{\mathcal{A}} \mathbf{Adv}^{\mathrm{AE}}_{\mathcal{E}}(\mathcal{A})$

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Motivation of this Work

Designing Highly Secure Lightweight AE

- The mode should be very light
- It should provide sufficient security level
- It should achieve better area-security trade-off among the existing designs

Designing Highly Secure Lightweight AE

Several Ways of Designing AE

- Blockcipher(BC) based
- Streamcipher (SC) based
- Permutation based (Sponge) etc.

Our target: Highly Secure Lightweight AE

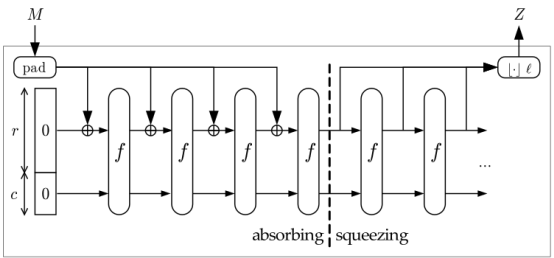
Best Choice: Sponge Based

- Sequential nonce-based AE
- b-bit state: r-bit *rate* + c-bit *capacity* ($b = r + c$)
- r-bit: process then feedback, c-bit: direct feedback

Sponge Mode

- Introduced as a hash mode with Keccak [a] hash (SHA-3)

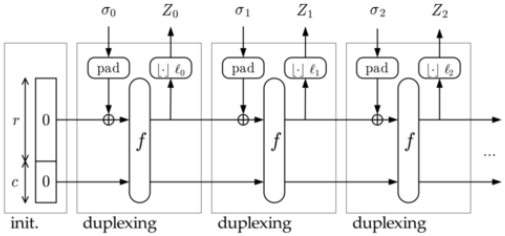
[a] Guido Bertoni, Joan Daemen, Michaël Peeters, and Gilles Van Assche, Keccak, In EUROCRYPT 2013



SpongeAE

- Sponge based AE designed in Duplex[a] mode
- $c/2$-bit AE security

[a] Guido Bertoni, Joan Daemen, Michaël Peeters, and Gilles Van Assche. Duplexing the sponge: Single-pass authenticated encryption and other applications, SAC 2011



Sponge Based AE

Improved Bound (Jovanovic et al's Result)

- Showed $min\{b/2, c\}$-bit AE security [a] of Duplex sponge
- Assumed number of decryption blocks $\leq 2^{c/2}$ (Impractical in real life)
- Essentially $c/2$-bit security remains (considering decryption blocks)

[a] Philipp Jovanovic, Atul Luykx, and Bart Mennink, Beyond $2^{c/2}$ security in sponge- based authenticated encryption modes, ASIACRYPT 2014

Main Challenge of This Work

- Main Difficulty: Ciphertext is injected directly to the permutation
- Can we stop that and increase the security adding simple tweaks in the design?

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3 Specification for Beetle
- Design of Beetle
- Security Bounds
- Properties

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Can we stop direct Ciphertext injection to the permutation

Possible Options for Feedback

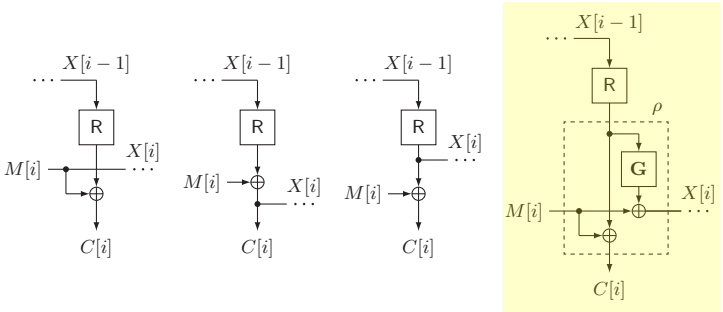
- Message Feedback: Current $M[i]$ is the feedback $X[i]$ for the next primitive call
- Ciphertext Feedback: Current $C[i]$ is the feedback $X[i]$
- Output Feedback: Previous primitive output $Y[i-1]$ is the feedback $X[i]$

Combined Feedback

- Exactly one of $M[i]$, $C[i]$, $Y[i-1]$ can not compute $X[i]$. Adversary can not control $X[i]$ (by enc/ dec queries). Introduced in COFB[a]

[a] Avik Chakraborti, Tetsu Iwata, Kazuhiko Minematsu and Mridul Nandi, Blockcipher Based Authenticated Encryption: How small can we go?, CHES 2017

Different Feedback Modes and COFB (Combined Feedback) Mode



Design Rationale and Challenges

Beetle: Uses Combined Feedback in the first r-bit

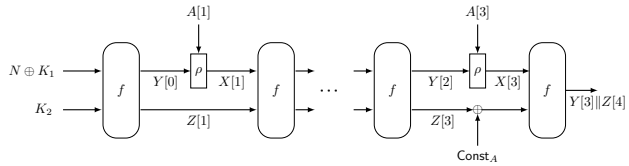
State Size

- It needs only a b bits for storing the permutation f state

Effect of Combined Feedback

- Each f output is processed with M using a combined feedback ρ
- $(X, C) = \rho(Y, M)$: X is influenced by both Y and M
- High security bound: due to feedback function, hard to forge

Beetle AE Mode



- $\text{Const}_M = 1$ if $M \neq \lambda$ and n divides $|M|$, $\text{Const}_M = 2$ else

Selection of ρ Function in Beetle

- $(X, C) = \rho(Y, M) = (\rho_1(Y, M), Y \oplus M)$, where
- $X = \rho_1(Y, M) := G \cdot Y \oplus M, \quad C = \mathbf{I} \cdot Y \oplus M$
- Both G and $G + \mathbf{I}$: Full rank matrix $\neq \mathbf{I}$
- During decryption: $X = (G + \mathbf{I}) \cdot Y + C$
- Distinction of G and $\mathbf{I}$ makes combined feedback

- $G : y = (y_1, y_2) \rightarrow (y_2, y_2 \oplus y_1)$ where $y_1, y_2 \in \{0, 1\}^{r/2}$
- Efficient to implement ($r/2$-bit left shift + $r/2$-bit XOR)

$$G_{r \times r} = \begin{pmatrix} \mathbf{0} & \mathbf{I} \\ \mathbf{I} & \mathbf{I} \end{pmatrix}$$

Instantiation of Beetle AE Mode

Recommended Versions

- Beetle[Light+]: Lightweight
- Beetle[Secure+]: High security level

Underlying f

- For Beetle[Light+]: *PHOTON*[a] P_{144} with $b = 144, r = 64, c = 80$
- For Beetle[Secure+]: *PHOTON* P_{256} with $b = 256, r = 128, c = 128$

[a] Jian Guo, Thomas Peyrin, and Axel Poschmann, The PHOTON family of lightweight hash functions, CRYPTO 2011

AE Security Level for Beetle Mode

AE Security Bound

- Nonce-*respecting* adversary
- min{b/2, c - logr, r} bit AE security
- Beetle[Light+] has 64-bit security
- Beetle[Secure+] has 121-bit security

Table: Comparative Study on the State size and Security Trade-off. Assume $r = c = b/2$

Design	State size	Security
Beetle	**b**	$\mathbf{b/2 - \log b/4}$
SpongeAE	b	$b/4$

Important Features of Beetle AE

Advantages

- Very low *state size* of b (b: state size)
- Very *flexible* mode (*any* permutation f can be used)
- *Inverse-free*
- *Simple* linear feedback
- Very lightweight and consumes *low* hardware area

Limitations

- *Both* the encryption and decryption are completely *serial*

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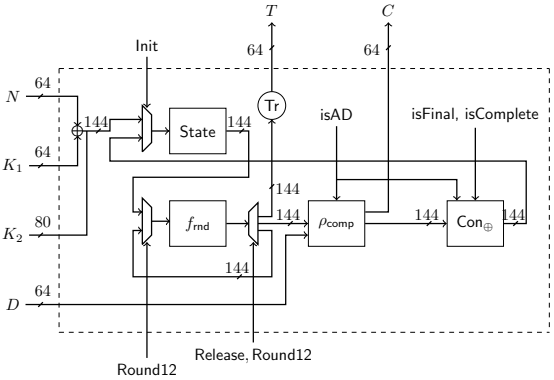
Cycles per Byte Performance of Beetle[Light+]

- a block AD, m block M ($r = 64$-bit blocks, i.e, 8 byte blocks)
- cycle count $= 13(a + m) + 12$ (In this calculation, we assume $a = m$)
- cpb $= \frac{cycle\_count}{len}$, len is length of M in bytes (actually $\frac{13 \times 2m + 12}{8m} = 3.25 + \frac{1.5}{m}$)

Table: Clock cycles per message byte for Beetle[Light+] with $r = 64$.

	Message length (Bytes)										
	8	16	24	32	64	128	256	512	1024	2048	16384
cpb	3.4375	3.3437	3.3125	3.2969	3.2734	3.2617	3.2559	3.2529	3.2514	3.2507	≈ 3.2500

Beetle[Light+] Base Architecture



Beetle[Light+] Base Architecture Properties

- Serial processing of data
- Round-based architecture of *PHOTON* P_{144} permutation
- Processes 64 bits per 12 clock cycles
- Uses very low storage registers (only b-bit)
- Minimum hardware area among all the known implementations

Beetle Implemented FPGA Results (VHDL, Xilinx 13.4)

Table: Beetle[Light+]. Not compatible with CAESAR API

Platform	# Slice Registers	# LUTs	# Slices	Frequency (MHZ)	Gbps	Mbps/ LUT	Mbps/ Slice
Vertex 6	185	616	252	381.592	1.879	3.050	7.369
Virtex 7	185	608	312	425.595	2.095	3.445	6.715

Table: Beetle[Secure+]

Platform	# Slice Registers	# LUTs	# Slices	Frequency (MHZ)	Gbps	Mbps/ LUT	Mbps/ Slice
Vertex 6	281	998	434	256.000	2.520	2.525	5.806
Vertex 7	305	1101	512	303.965	2.993	2.718	5.846

Benchmarking Beetle[Light+] on Virtex 6

We admit our implementation does not follow CAESAR API

Scheme	Underlying Primitive	Security (in Bits)	# LUTs	# Slices	Gbps	Mbps/ LUT	Mbps/ Slice
Beetle[Light+]	**Sponge(144, 64)**	64	**616**	**252**	**1.879**	**3.050**	**7.369**
Ketje-JR	Sponge(200, 16)	96	1236	412	2.832	2.292	6.875
ASCON-128	Sponge(320, 64)	128	1274	451	3.118	2.447	6.914
JAMBU-SIMON96	BC(64)	48	1035	386	0.931	0.899	2.411
CLOC-TWINE80	BC(80)	32	1689	532	0.343	0.203	0.645
SILC-LED80	BC(80)	32	1684	579	0.245	0.145	0.422
SILC-PRESENT80	BC(80)	32	1514	548	0.407	0.269	0.743
COFB-AES	BC(128)	58	1075	442	2.850	2.240	6.450

Benchmarking Beetle[Secure+] on Virtex 6

Scheme	Underlying Primitive	Security (in Bits)	# LUTs	# Slices	Gbps	Mbps/ LUT	Mbps/ Slice
Beetle[Secure+]	**Sponge(256, 128)**	**121**	**998**	**434**	**2.520**	**2.525**	**5.806**
ASCON-128	Sponge(320, 64)	128	1274	451	3.118	2.447	6.914
NORX	Sponge(1024, 768)	128	5495	1724	24.524	4.463	9.139
Ketje-SR	Sponge(400, 32)	128	1903	613	5.772	3.033	9.416
Riverkeyak	Sponge(800, 544)	128	6234	1751	7.417	1.190	4.236
Lakekeyak	Sponge(1600, 1344)	128	19860	7130	12.603	0.635	1.768
Gibbon	Sponge(280, 40)	120	1807	653	1.280	0.708	1.960
Hanuman	Sponge(280, 40)	120	1769	626	0.693	0.392	1.107
ICEPOLE128a	Sponge(1280, 1024)	128	5734	1995	44.464	7.754	22.288

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Conclusion

- Beetle : Permutation based *AE* mode
- Security level: min{b/2, c- log r, r}
- *Low area* AE and can be used in low resource *embedded devices*




Thank You..!!!