# Breaking REMUS and TGIF

N.Datta, A.Jha, A.Mege*, M.Nandi

Indian Statistical Institute, Kolkata, India
*Airbus Defence and Space, Elancourt, France

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# NIST LwC Security Requirements

Call for submission Draft

- Cryptanalytic attacks on the AEAD algorithm shall require at least $2^{112}$ computations on a classical computer in a single-key setting.
- The limits on the input sizes (plaintext, associated data, and the amount of data that can be processed under one key) for this member shall not be smaller than $2^{50} - 1$ bytes.

# NIST LwC Security Requirements

- $D$ (data complexity): the maximum amount of data processed under one key.
- $T$ (time complexity): total number of computations done.

**Minimum security requirements from an AEAD scheme $\Psi$**

If $D < 2^{50}$ bytes and $T < 2^{112}$, then $\Psi$ is *secure*.

# A Note on the Data Complexity

## The Data Limit (Data Complexity of an attack)

- Quantifies the online (queries to the AEAD scheme) resource requirements.
- Includes the total number of blocks (among all messages/ciphertexts and associated data) processed through the underlying primitive for a fixed master key.

## The Computation Time (Time Complexity of an attack)

- Quantifies the offline resource requirements, and includes the total time required to process the offline evaluations of the underlying block cipher.
- The number of primitive evaluations is taken as the time complexity of evaluations.

# A Note regarding the Time Complexity

The direct evaluations of the primitives have been considered within time complexity in multiple papers:

- The time-memory trade-off attack by Hellman [Hellman, 80],
- Related-key attacks on AES-256 [Biryukov+, 09],
- Attacks on hash functions [Kelsey+ 05, 06, Guo+ 14, Andreeva+ 16],
- Attacks on HMAC and NMAC [Peyrin+ 12, Leurent+ 13, Peyrin+ 14, Guo+ 14, Dinur+ 17],
- Attacks on Even-Mansour ciphers [Dunkelman+ 12, Dinur+ 13, Dinur+ 14, Dunkelman+ 15], and
- Multi-key attacks on Even-Mansour cipher [Mouha+ 15].

In fact, this also makes sense in real scenario, where the adversary can actually make block cipher evaluations on its own by devoting sufficient time.

# The Crucial Observation

## Main Observation on REMUS and TGIF

- REMUS-N1, REMUS-N3, REMUS-M1, TGIF-N1, and TGIF-M1 restrict the number of offline evaluations of the underlying block cipher to less than $2^{64}$.
- This clearly violates the NIST LwC requirements as stated above, as the adversary is allowed make beyond $2^{64}$ (anything below $2^{112}$ is valid) block cipher evaluations.
- This is especially required from REMUS-N1 and TGIF-N1, which are the primary variants in their respective submissions.

# Revisiting the Multi-Key Attack [Mouha+ 15]

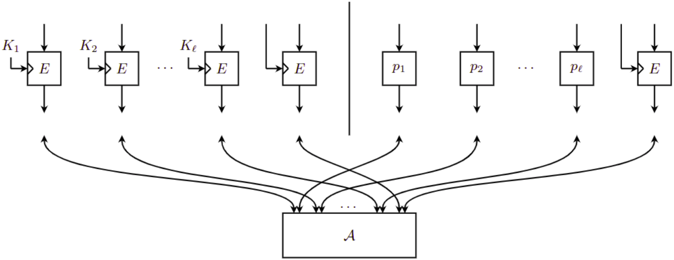



Figure: An ideal block cipher $E_K$ in the multi-key setting.

# Revisiting the Multi-Key Attack [Mouha+ 15]

### Make the Off-line Queries

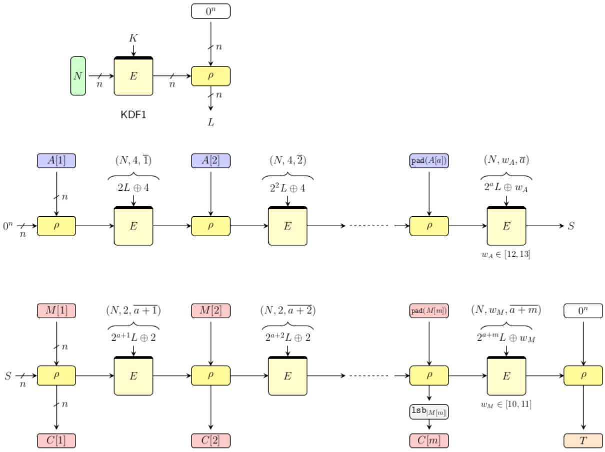
- Choose $K^0, \ldots, K^{T-1}$ without replacement.
- For $i = 0, \ldots, (T-1)$, simulate the encryption of $M$ using $K^i$, and store the responce $(K^i, C^i)$ in a list $H$.

### Make the On-line Queries

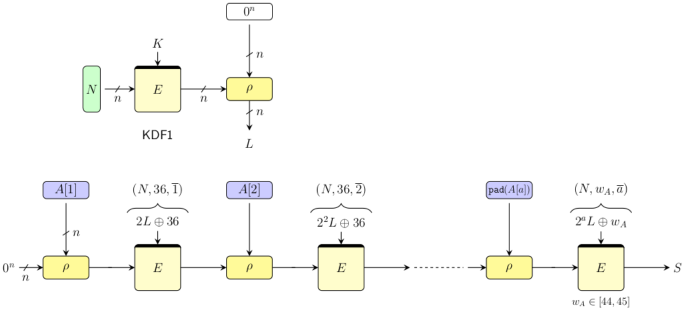
- Query $M$ under $D$ many independent keys. Let the outputs be $\hat{C}^0, \ldots, \hat{C}^{D-1}$.
- If $C^i = \hat{C}^j$ (matching occurs), recover the key $K^i$ (with high probability).

- Matching occurs with probability $DT/2^n$.

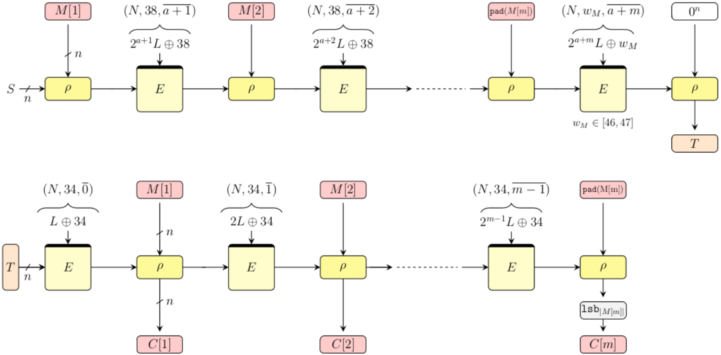
# Specification of REMUS-N1 and TGIF-N1



# Specification of REMUS-M1 and TGIF-M1



# Specification of REMUS-M1 and TGIF-M1



# Key Derivation Functions for REMUS -N1/M1 and TGIF -N1/M1

## Choice of Parameters

- Block and key size is set to $n = 128$.
- Nonce size is also set to $r = 128$.

## The Key Derivation Function

Takes a nonce $N$ as input and outputs a nonce-based key $L$:

$$\mathrm{KDF}_K(N) := E_K(N).$$

# Algorithm 1: Find the Nonce-based Key for REMUS -N1/M1 and TGIF -N1/M1

### Step 1: Make the Off-line Queries

- Choose $L^0, \ldots, L^{2^t-1}$ without replacement.
- For $i = 0, \ldots, (2^t - 1)$, simulate the encryption of $(A, M)$ using $L^i$ as the nonce-based key, where $|A| = |M| = n$. Response: $(C^i, \tau^i)$. Store $(L^i, C^i, \tau^i)$ in a list $H$.

### Step 2: Sort the List

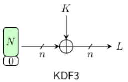
Sort entries in $H$ on second and third coordinates, i.e. $(C, \tau)$.

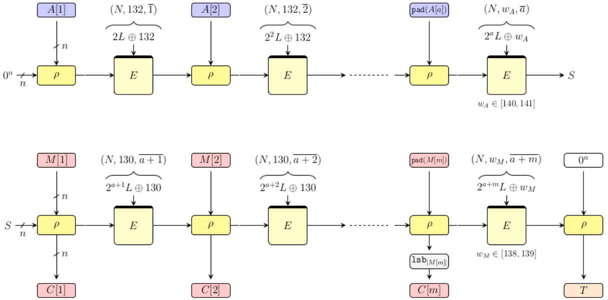
# Algorithm 1: Find the Nonce-based Key for REMUS -N1/M1 and TGIF -N1/M1

### Step 3: Make the On-line Queries and Find Matching

- Choose distinct nonces $\hat{N}^0, \ldots, \hat{N}^{2^t-1}$.
- For $j = 0, \ldots, 2^d - 1$, query $(\hat{N}^j, A, M)$ to the encryption oracle of AEAD. Let the response be $(\hat{C}^j, \hat{\tau}^j)$.
- Search $(\hat{C}^j, \hat{\tau}^j)$ in $H$. If $\exists i \in H$ such that $(\hat{C}^j, \hat{\tau}^j) = (C^i, \tau^i)$ then $\hat{L}^j = L^i$ with very high probability.

# Specification of REMUS-N3



# Key Derivation Functions for REMUS-N3

## Choice of Parameters

- Block and key size is set to $n = 128$.
- Nonce size is set to $r = 96$.

## The Key Derivation Function

Takes a nonce $N$ as input and outputs a nonce-based key $L$:

$$\mathsf{KDF}_K(N) := K \oplus N \| 0^{32}.$$

# Extended Algorithm 1: Find the Nonce-based Key for REMUS-N3

- Set the following parameters: $t \geq 32$, $d = n - t$.
- Define $L^i := 0^d \| \langle i \rangle_t$, where $\langle i \rangle_t$ denotes the $t$-bit representation of integer $i$.
- Define $\hat{N}^j = \langle j \rangle_d \| 0^{r-d}$. Note that $r - d \geq 0$ due to $t \geq 32$.
- Invoke Algorithm 1 with this modified $L^i$'s and $\hat{N}^j$'s.

# Key Recovery Attack against REMUS-N3

- Use Algorithm 1 to obtain a nonce-based key pair $(N', L')$.
- Recover the master key $K = L' \oplus N' \| 0^{32}$.

# Forgery against REMUS -N1/N3/M1 and TGIF -N1/M1

## Nonce-respecting forgery attacks

- Use Algorithm 1 to obtain a nonce-based key pair $(N', L')$.
- Construct valid forgeries of the form $(N', A', C', T')$, where $A'$ and $C'$ can be chosen arbitrarily, and the tag is computed using $L'$, $A'$ and $C'$.
- This attack is applicable on REMUS-N1 (primary version), REMUS-N3, and REMUS-M1 as well as TGIF-N1 (primary version) and TGIF-M1.

# Complexity of the Attack

- Data complexity, $D \approx 2^{d+5.6}$ bytes. The factor of 5.6 is due to the fact that each encryption query consists of $3 \approx 2^{1.6}$ blocks of data and each block contains $2^4$ bytes.
- Total time complexity, $T \approx 2^{t+5.6} + t \cdot 2^t + t \cdot 2^{n-t}$.

## Choices of $d$ and $t$

- The algorithm works for all choices of $t \geq 32$, as $d + t = 128$.
- Set $t = 90$, which gives $d = 38$.
- For this choice of $t$, we obtain $D \approx 2^{43.6}$ bytes and $T \approx 2^{97.5}$, which clearly falls within the NIST LwC minimum data and time limit.

# Possible Improvements

- Use a hash table instead of a list.
- Improve data complexity by using empty message and empty AD. However, this may lead to some false positives which can be eliminated by making constant number of checking queries.
- Note: We do not use the empty message and AD case, as such inputs seldom occur in real scenario.

# Inherent Weakness of REMUS-N1/N3/M1 and TGIF-N1/M1

**Insufficient randomness in the initial state (key, input)**

- Although the key is derived using nonce for each encryption query, the adversary can easily fix a constant value as the initial input.
- To create an initial state collision, the adversary just needs to collide the initial key.

- Use of nonce in the beginning of AD processing would have prevented the above attack.
- This attack is not possible for REMUS-N2/M2 and TGIF-N2/M2 due to the larger state.

Thank You..!! Questions??