CASA

Cyber Security in the Age of Large-Scale Adversaries

Cryptanalysis of HALFLOOP Block Ciphers: Destroying HALFLOOP-24

FSE 2024, Leuven, March 25

Gregor Leander, Shahram Rasoolzadeh and Lukas Stennes

RUHR UNIVERSITÄT BOCHUM RUB

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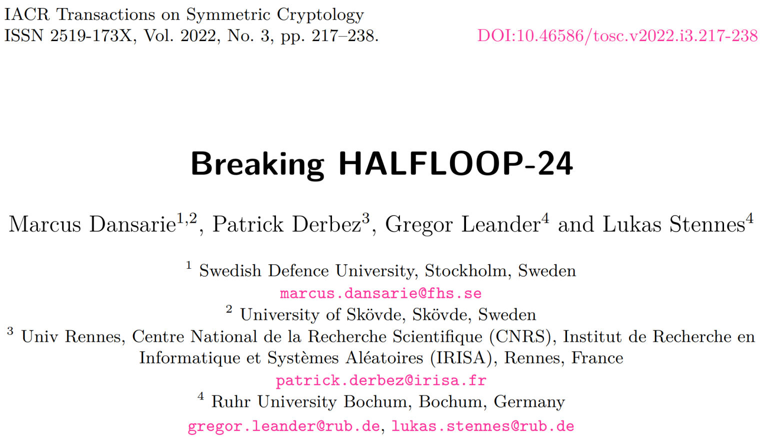

IACR Transactions on Symmetric Cryptology
ISSN 2519-173X, Vol. 2022, No. 3, pp. 217–238.
DOI:10.46586/tosc.v2022.i3.217-238

Breaking HALFLOOP-24

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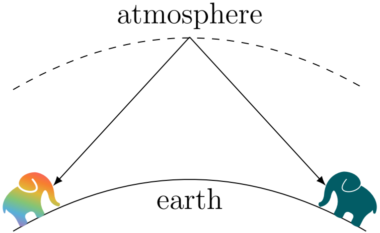
Why HALFLOOP: High Frequency Radio

- Frequencies between 3MHz and 30MHz
- Skywave propagation: radio signals are reflected by upper atmosphere
- Enables communication across very large distances without any external infrastructure
- Users are the military, diplomatic services, disaster management agencies, etc.
- HALFLOOP is used for encrypting handshake messages (confidentiality and authentication)



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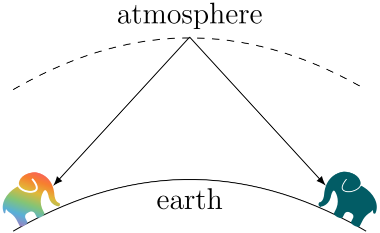

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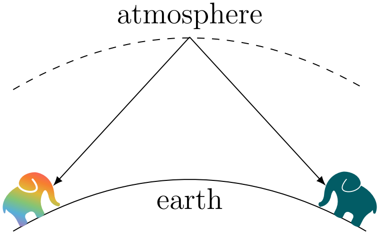

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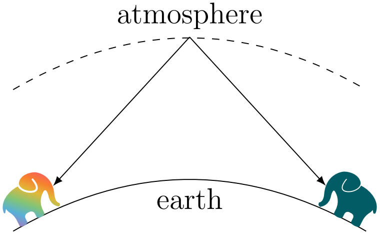

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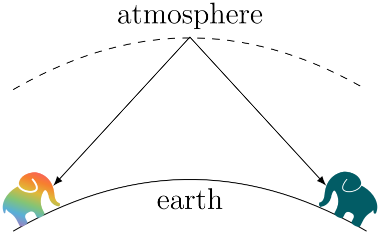
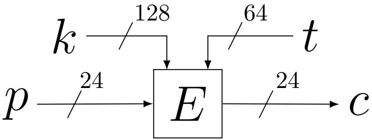


Description of HALFLOOP-24 (HALFLOOP-$\{48{,}96\}$ work similarly)

Description of HALFLOOP-24 – Big Picture

- HALFLOOP-24 is a tweakable block cipher E
  - Tweak consists of current time, a word counter and the used frequency
  - Supersedes SoDark cipher which used **56-bit** keys
  - Specified in MIL-STD-188-141 since **2017**
- HALFLOOP-24 is heavily inspired by AES
  - Uses the same SBox
  - Essentially the same key schedule
  - State is represented as 3×1 matrix over $\mathbb{F}_{2^8}$
  - 10 rounds



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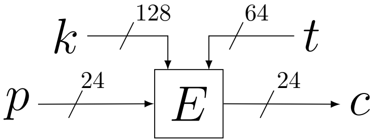

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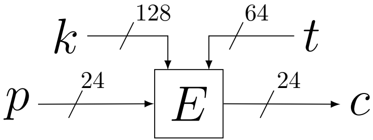

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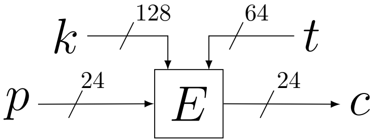

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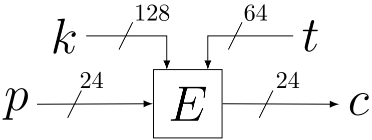

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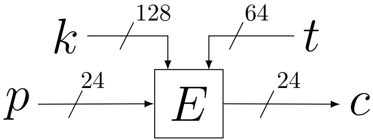

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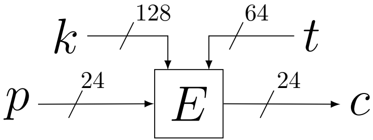

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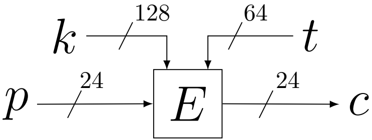

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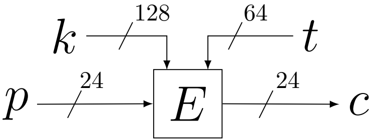
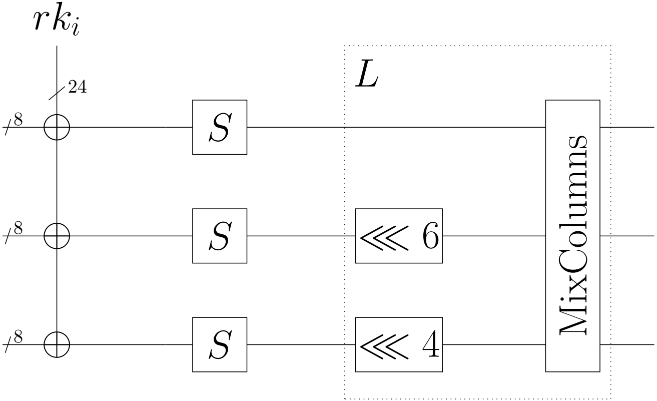
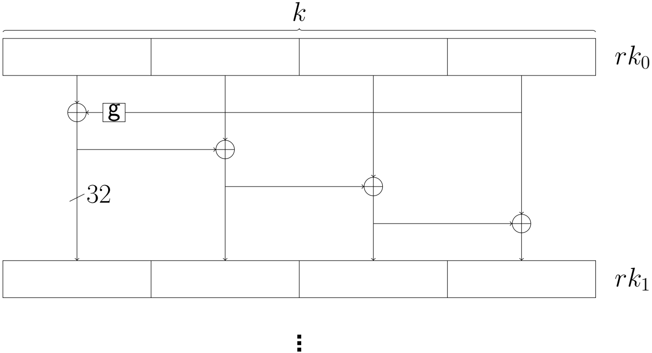


Description of HALFLOOP-24 – Round Function



MC: multiply with $c(x) = x^2 + 2x + 9$ modulo $x^3 + 1$

Description of HALFLOOP-24 – AES-128 Key Schedule



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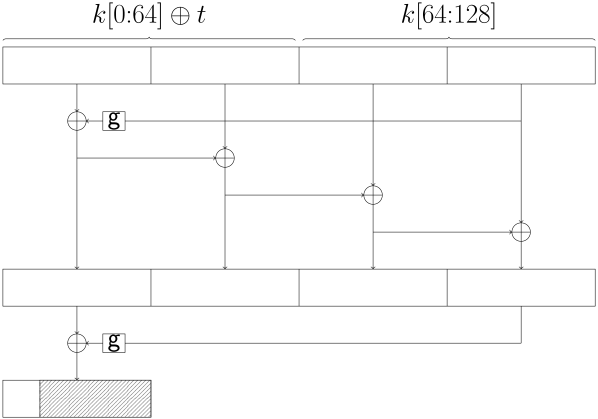

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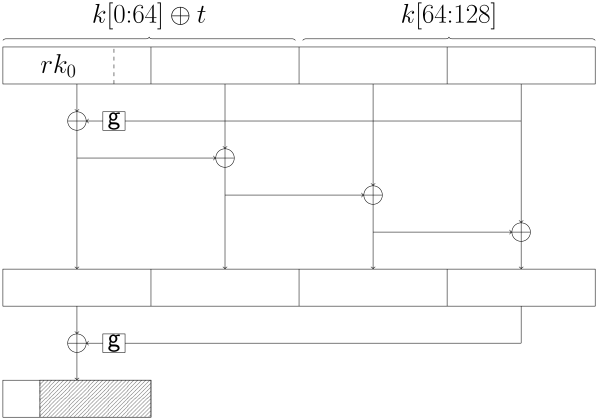

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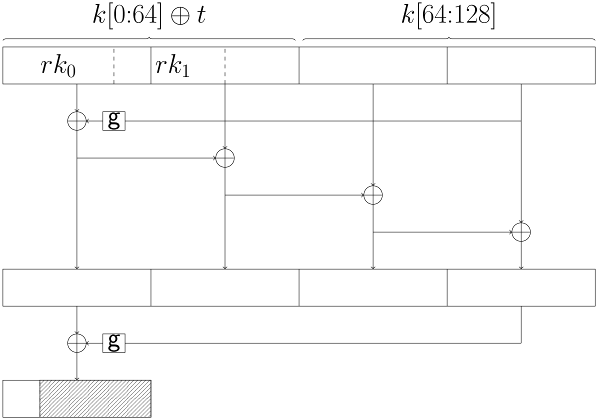

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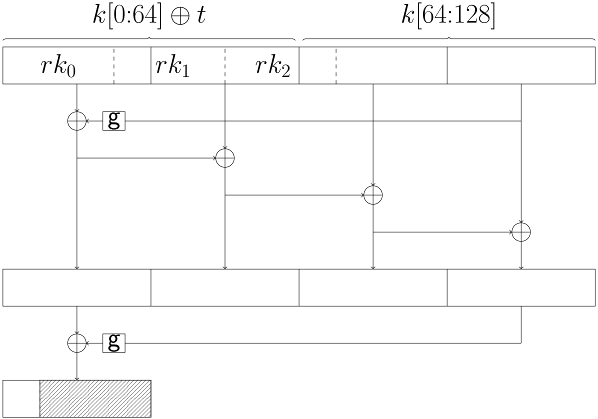

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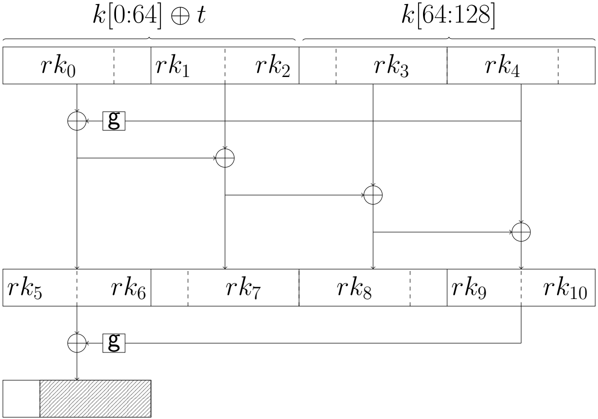

Generic Attack on HALFLOOP-{24,48,96}
(already pointed out by [LRW02, DDLS22])

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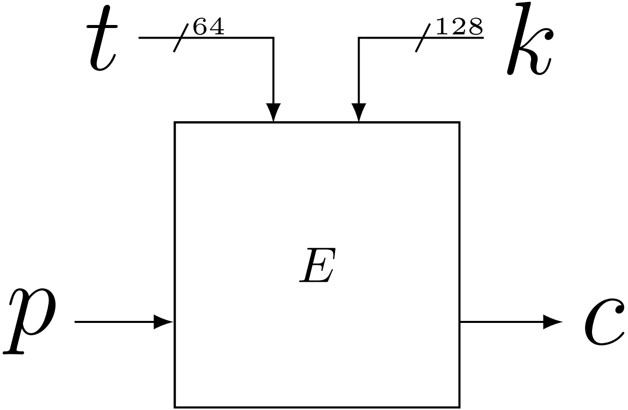

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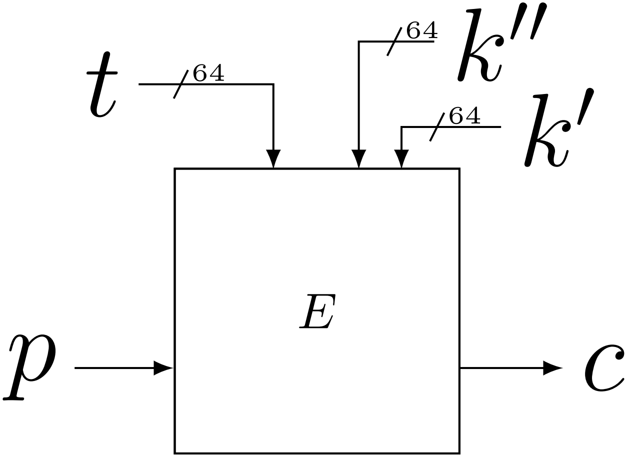

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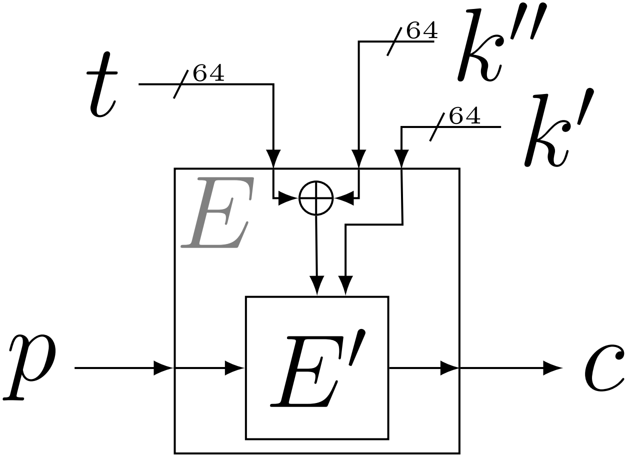

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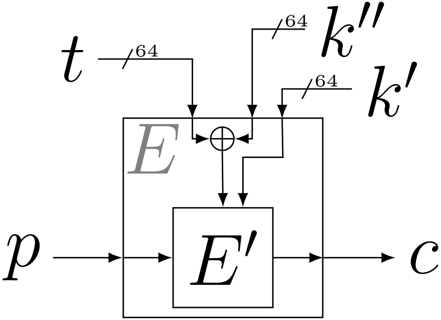

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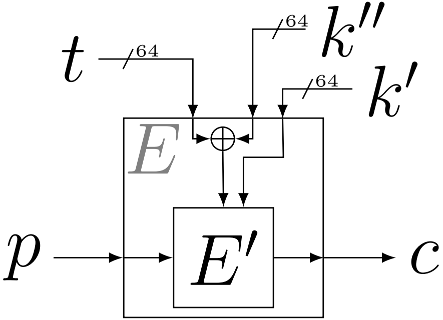

Offline Phase:

```
$T = [\,]$
for all $k' \in \mathbb{F}_2^{64}$:
    $c = E'_{0||k'}(p)$
    append $(k', c)$ to $T$
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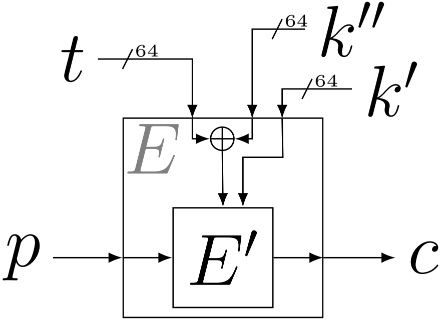

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Online Phase:

```
for all $t \in \mathbb{F}_2^{64}$:
    $c = E(t, p)$
    if $\exists k' s.t. (k', c) \in T$:
        key candidate $t||k'$
```

Attacks on HALFLOOP-24 – So Far

Setting	Time	Data	Memory	Reference
CPA	2^{65}	2^{64}	2^{64}	[DDLS22]
CCA	2^{10}	2^{10}	negligible	[DDLS22]
CPA	2^{56}	2^{18}	2 MB	[DDLS22]
ALE	2^{56}	**541 years**	2 MB	[DDLS22]

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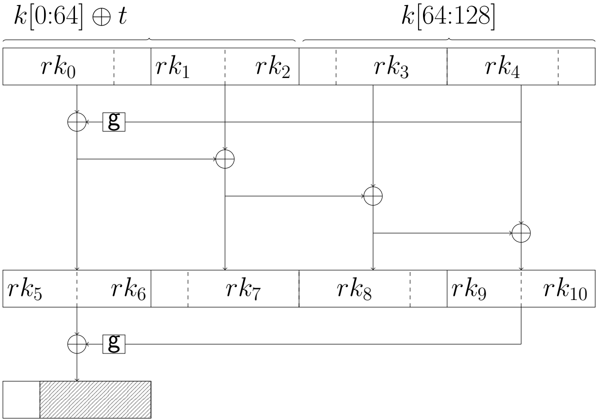
New Attack on HALFLOOP-24
(with minimal data)

New Attack on HALFLOOP-24 – Old Related Tweak in Key Schedule



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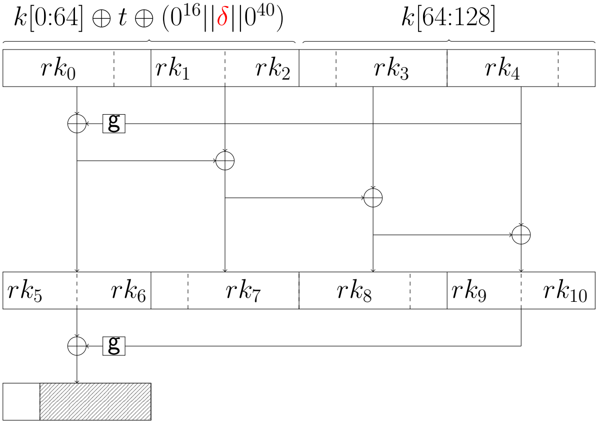

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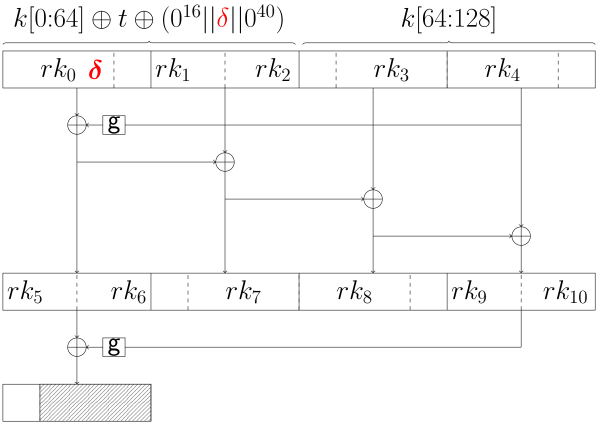

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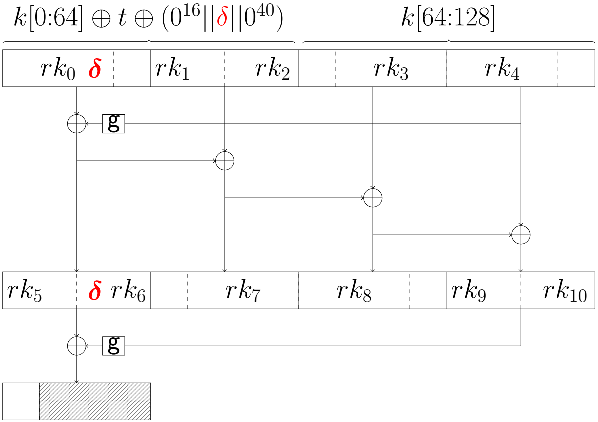

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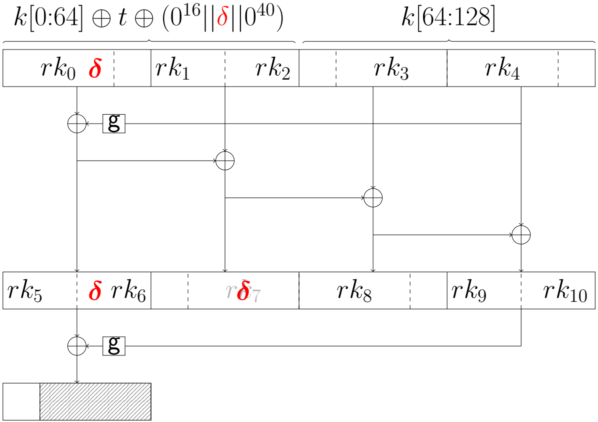

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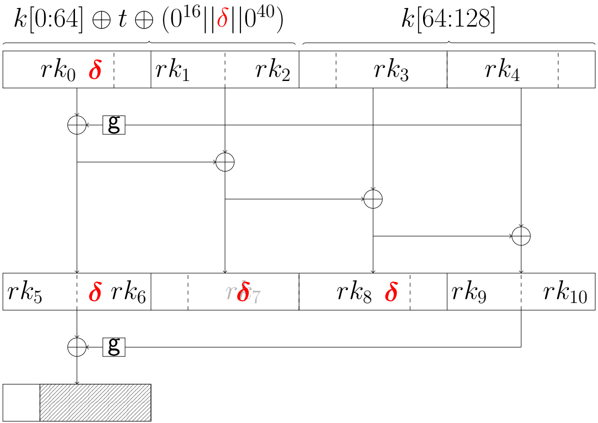
$k[0{:}64] \oplus t \oplus (0^{16}||\delta||0^{40})$
$k[64{:}128]$
rk_0 $\boldsymbol{\delta}$
rk_1
rk_2
rk_3
rk_4
g
rk_5
$\boldsymbol{\delta}$ rk_6
rk_7 $\boldsymbol{\delta}$
rk_8 $\boldsymbol{\delta}$
rk_9
rk_{10}
g

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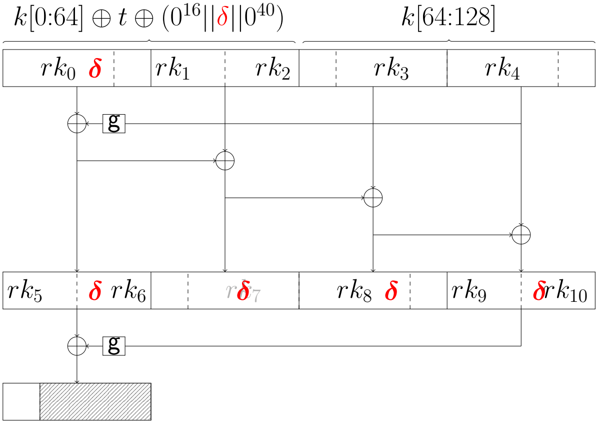

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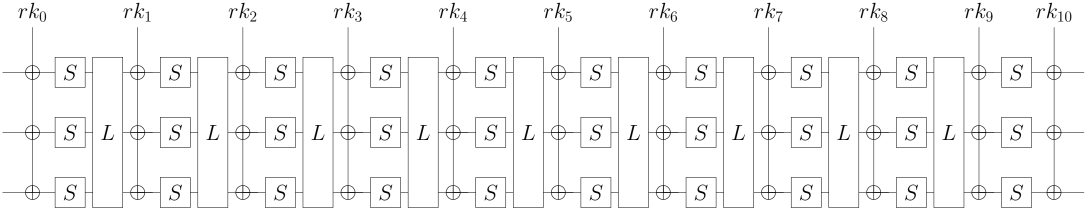

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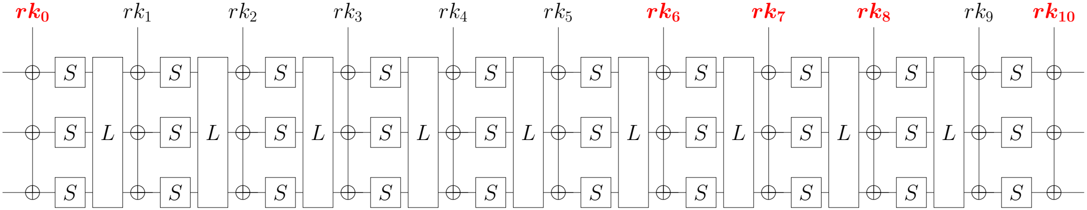

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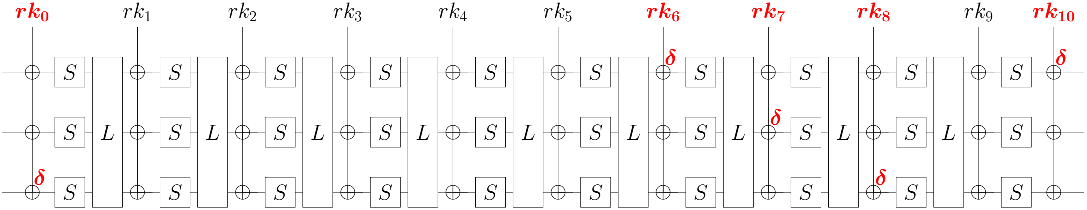

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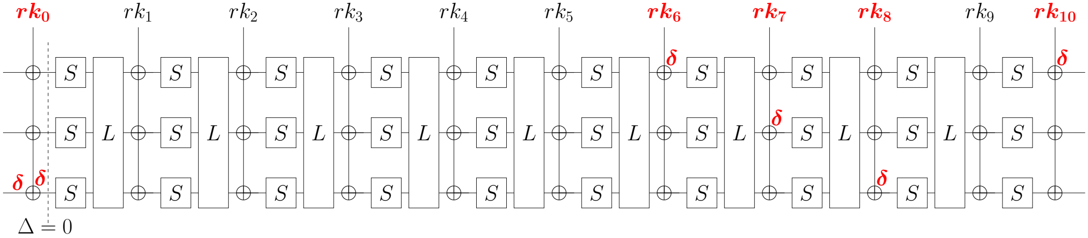

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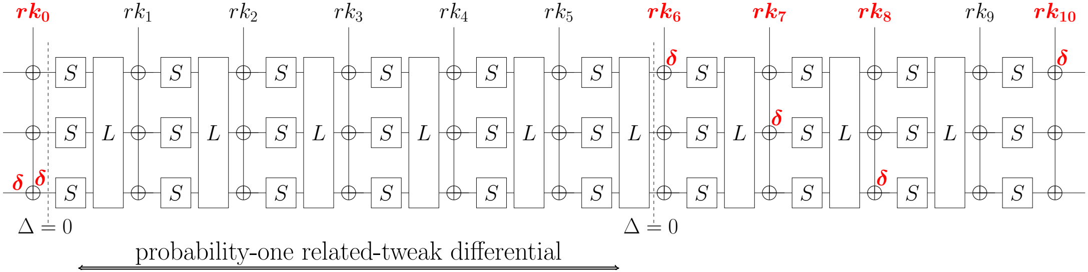

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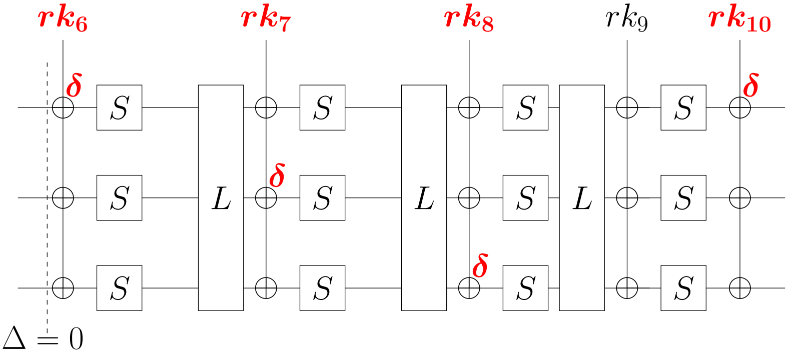

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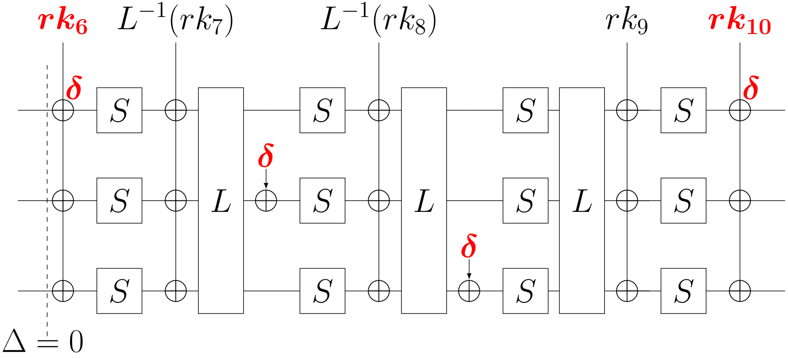

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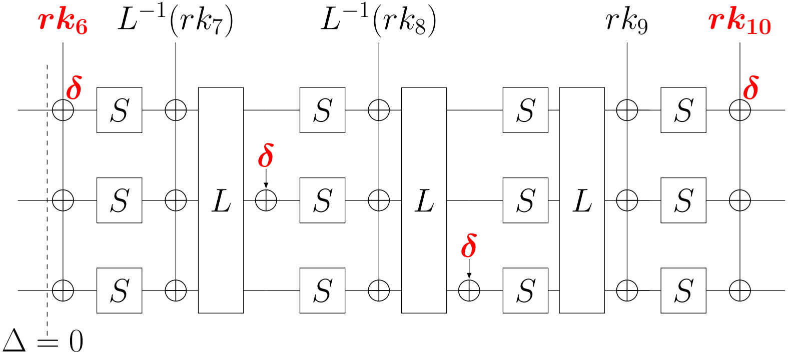
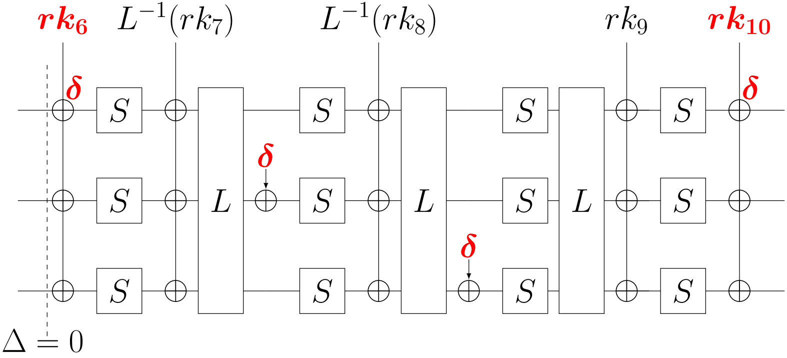


$\Rightarrow$ trivial attack with $t = 2^{80}$ and $D = 6$ (CPA)

New Attack on HALFLOOP-24



$\Rightarrow$ improved attack with $t = 2^{56}$ and $D = 6$ (CPA)

Attacks on HALFLOOP-24 – Overview

Setting	Time	Data	Memory	Reference
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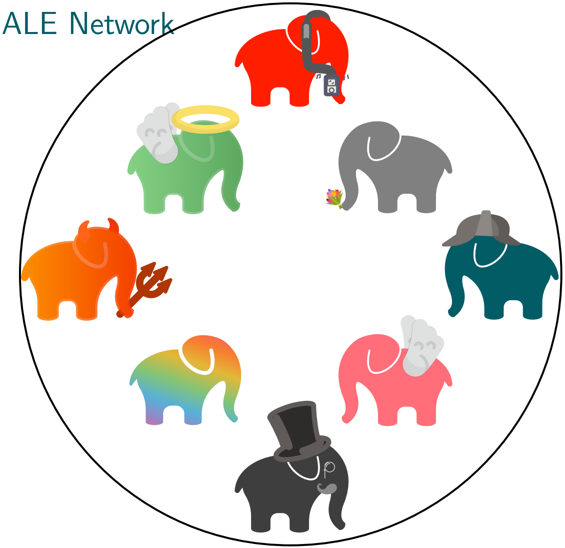
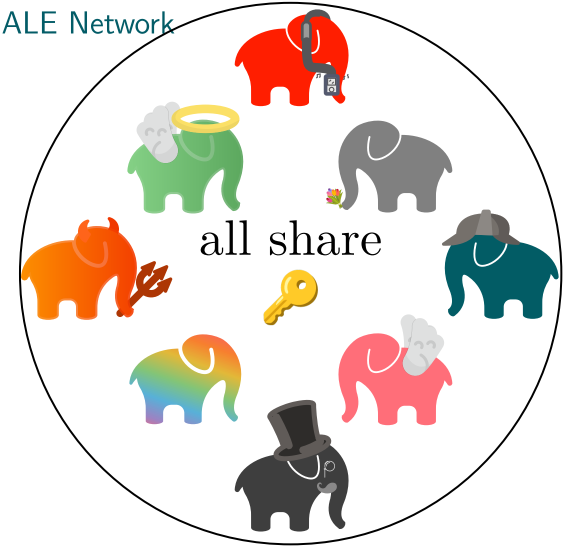
CPA	2^{56}	2^{18}	2 MB	[DDLS22]
ALE	2^{56}	**541 years**	2 MB	[DDLS22]
CPA	2^{56}	6	5 GB	This Work
CPA	2^{48}	8	5 GB	This Work
ALE	2^{48}	**2 hours**	5 GB	This Work

Attack in Practice – **A**utomatic **L**ink **E**stablishment

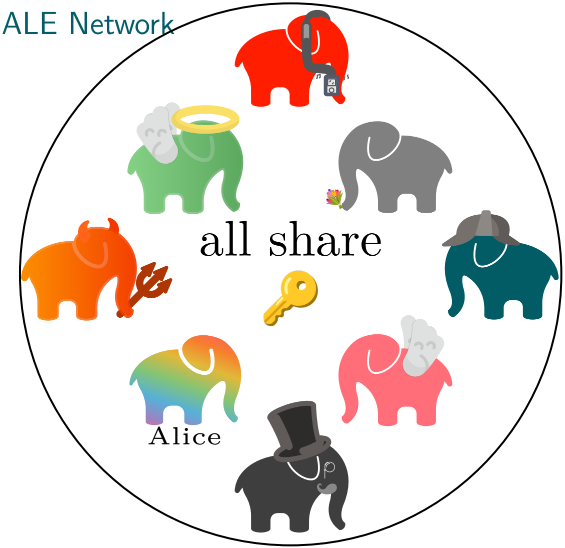
Attack in Practice – ALE Network



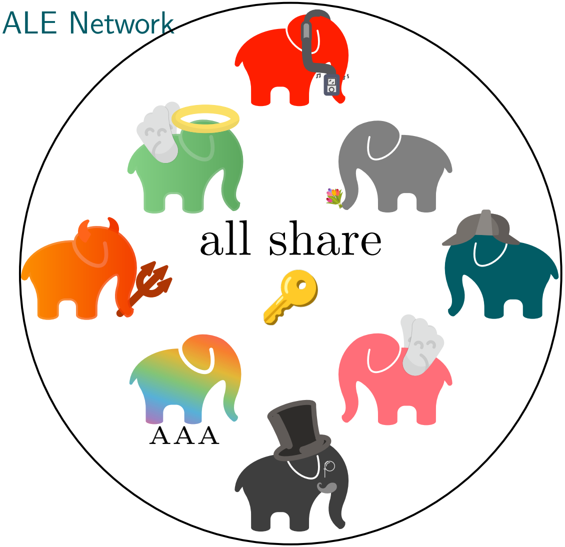
Attack in Practice – ALE Network



Attack in Practice – ALE Network

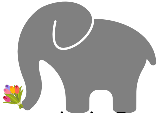


Attack in Practice – ALE Network



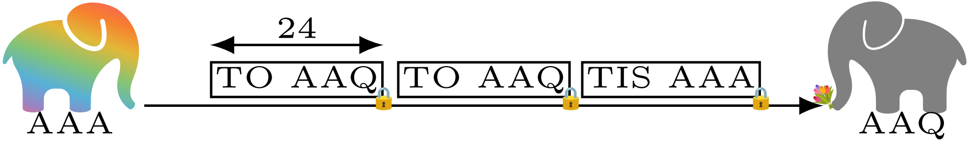
Attack in Practice – ALE Handshake

AAA

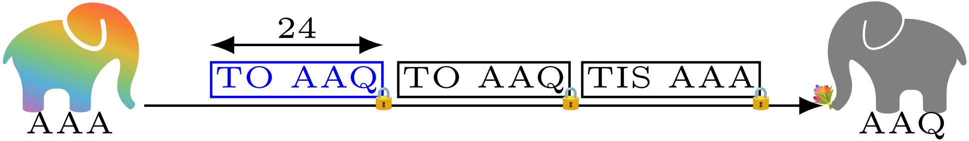


AAQ

Attack in Practice – ALE Handshake



Attack in Practice – ALE Handshake



24

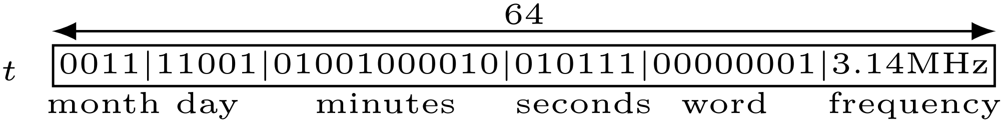
TO AAQ

TO AAQ

TIS AAA

AAA

AAQ



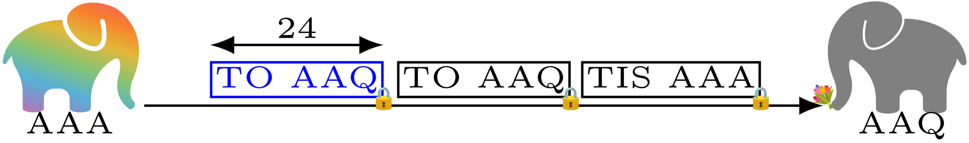
64

t

0011 | 11001 | 01001000010 | 010111 | 00000001 | 3.14MHz

month day minutes seconds word frequency

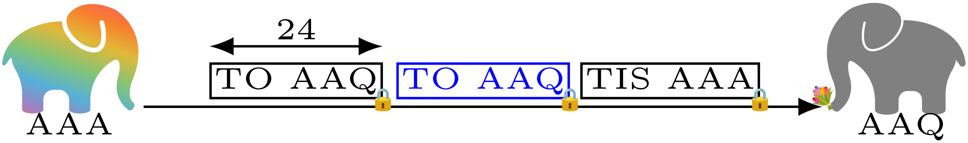
Attack in Practice – ALE Handshake



64

t	0011	11001	01001000010	010111	00000001	3.14MHz
	month	day	minutes	seconds	word	frequency

Attack in Practice – ALE Handshake



24

TO AAQ

TO AAQ

TIS AAA

AAA

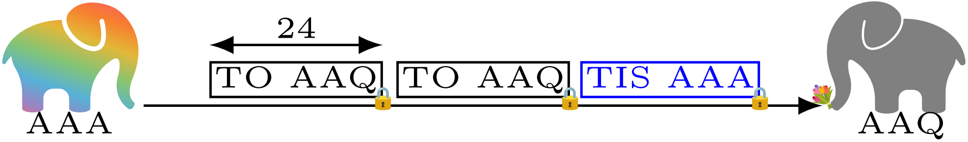
AAQ

64

t $\boxed{0011|11001|01001000010|010111|00000010|3.14\text{MHz}}$

month day minutes seconds word frequency

Attack in Practice – ALE Handshake

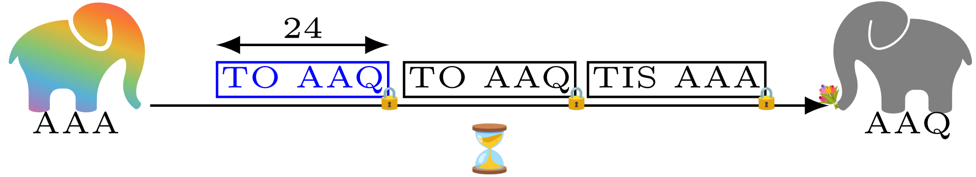


64

t

0011	11001	01001000010	010111	00000011	3.14MHz
month	day	minutes	seconds	word	frequency

Attack in Practice – ALE Handshake



24

TO AAQ

TO AAQ

TIS AAA

AAA

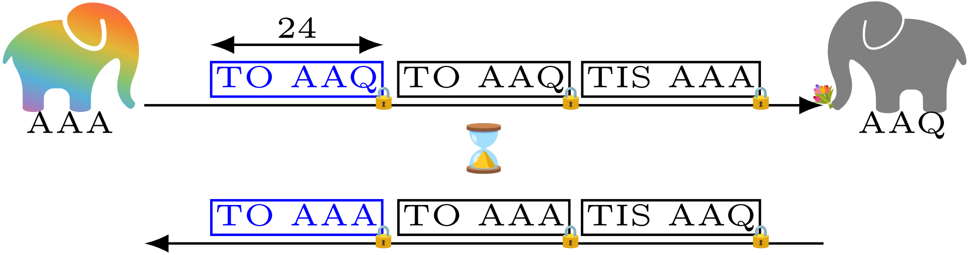
AAQ

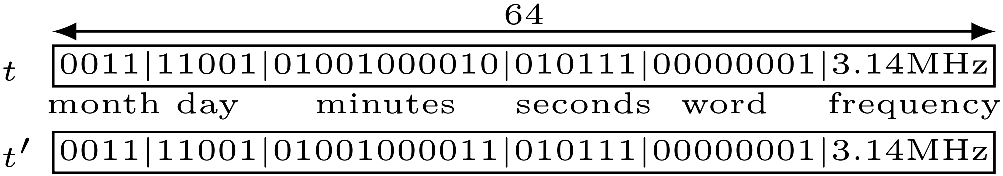
64

t 0011|11001|01001000010|010111|00000001|3.14MHz

month day minutes seconds word frequency

Attack in Practice – ALE Handshake



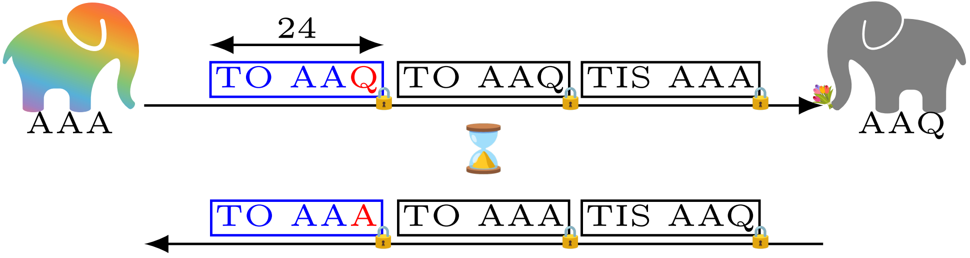


t: 0011|11001|0100100010|010111|00000001|3.14MHz

month day minutes seconds word frequency

t': 0011|11001|0100100011|010111|00000001|3.14MHz

Attack in Practice – ALE Handshake



24

AAA

TO AAQ | TO AAQ | TIS AAA

AAQ

TO AAA | TO AAA | TIS AAQ

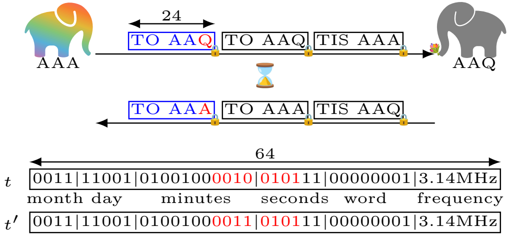
64

t 0011|11001|01001000010|010111|00000001|3.14MHz

month day minutes seconds word frequency

t' 0011|11001|01001000011|010111|00000001|3.14MHz

Attack in Practice – ALE Handshake

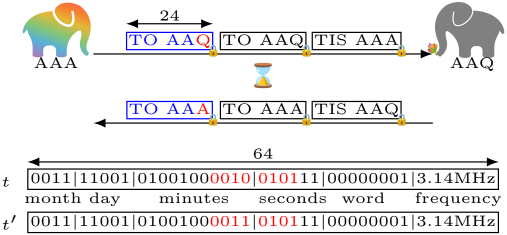


24
TO AAQ
TO AAQ
TIS AAA
AAA
AAQ
TO AAA
TO AAA
TIS AAQ
64
t
0011|11001|01001000010|010111|00000001|3.14MHz
month day
minutes
seconds
word
frequency
t′
0011|11001|01001000011|010111|00000001|3.14MHz

we get a good pair if

- frequencies are the same
- word counters are the same
- messages are sent in the same 16 minute bin
- seconds are the same modulo 4
- difference in remaining time matches difference in callsigns

Attack in Practice – ALE Handshake



AAA

24

TO AAQ | TO AAQ | TIS AAA

AAQ

TO AAA | TO AAA | TIS AAQ

64

t 0011|11001|01001000010|010111|00000001|3.14MHz

month day minutes seconds word frequency

t' 0011|11001|01001000011|010111|00000001|3.14MHz

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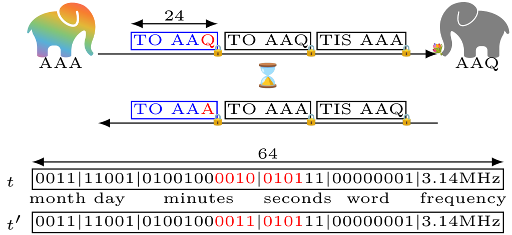
Attack in Practice – ALE Handshake



24

AAA — TO AAQ | TO AAQ | TIS AAA → AAQ

TO AAA | TO AAA | TIS AAQ ←

64

t 0011|11001|01001000010|010111|00000001|3.14MHz

month day minutes seconds word frequency

t' 0011|11001|01001000011|010111|00000001|3.14MHz

we get a good pair if

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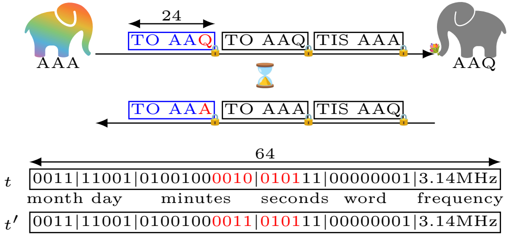
Attack in Practice – ALE Handshake



	month	day	minutes	seconds	word	frequency
t	0011	11001	01001000010	010111	00000001	3.14MHz
t'	0011	11001	01001000011	010111	00000001	3.14MHz

we get a good pair if

- frequencies are the same
- word counters are the same
- messages are sent in the same 16 minute bin
- seconds are the same modulo 4
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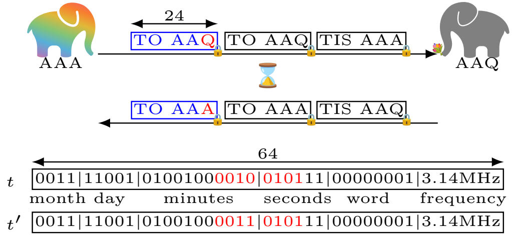
Attack in Practice – ALE Handshake


24
TO AAQ
TO AAQ
TIS AAA
AAA
AAQ
TO AAA
TO AAA
TIS AAQ
64
t
0011|11001|01001000010|010111|00000001|3.14MHz
month day
minutes
seconds
word
frequency
t′
0011|11001|01001000011|010111|00000001|3.14MHz

we get a good pair if

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- word counters are the same
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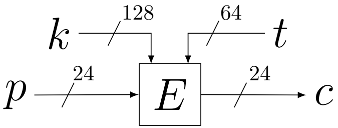
- seconds are the same modulo 4
- difference in remaining time matches difference in callsigns

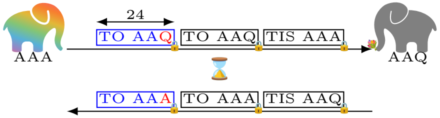
Attacks on HALFLOOP-$\{48{,}96\}$

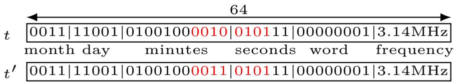
Attacks on HALFLOOP-{48,96} – Overview

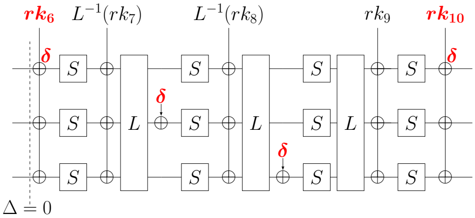
Variant	Attack	Time	Data	Memory
HALFLOOP-48	Generic	2^{65}	2^{64}	$3 \cdot 2^{29}$ TB
HALFLOOP-48	DS-MITM	2^{122}	13	2^{57} TB
HALFLOOP-96	Generic	2^{65}	2^{64}	$3 \cdot 2^{29}$ TB
HALFLOOP-96-7r	DS-MITM	2^{114}	15	2^{105}

Conclusion



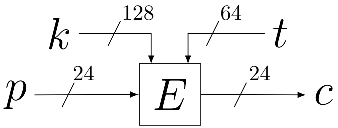


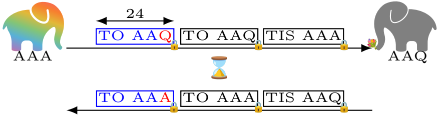

64
t
0011|11001|0100100010|010111|00000001|3.14MHz
month
day
minutes
seconds
word
frequency
t′
0011|11001|0100100011|010111|00000001|3.14MHz

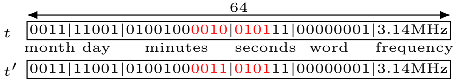


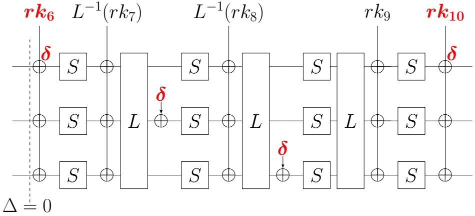
Setting	Time	Data	Memory	Reference
CCA	2^{10}	2^{10}	negligible	[DDLS22]
CPA	2^{56}	2^{18}	2 MB	[DDLS22]
ALE	2^{56}	**541 years**	2 MB	[DDLS22]
CPA	2^{56}	6	5 GB	This Work
CPA	2^{48}	8	5 GB	This Work
ALE	2^{48}	**2 hours**	5 GB	This Work

Conclusion






64
t 0011|11001|0100100010|010111|00000001|3.14MHz
month day minutes seconds word frequency
t' 0011|11001|0100100011|010111|00000001|3.14MHz



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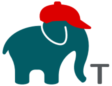

Thank You!