Dismantling Megamos Crypto: Wirelessly Lockpicking a Vehicle Immobilizer

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Why this special paper presentation?

- This paper was first accepted at Usenix Security'13
- VW sought an injunction from the High Court of London to prevent publication
- The High Court of London granted an interim injunction and therefore we had to withdraw the article
- We have now reached an amicable settlement without any admission of liability
- We will talk about the technical content of the paper but not about the details of the case

Vehicle Immobilizers

- Passive RFID Tags (125 KHz)
- Prevent hot-wiring
- Mandatory
  - Europe (EU Directive 95/56/EC)
  - Australia (AS/NZS 4601:1999)
  - Canada (CAN/ULC S338- 98)
- Prevent insurance fraud
- Should not be confused with remote controls that unlock the car doors (433 MHz)

Vehicle Immobilizers

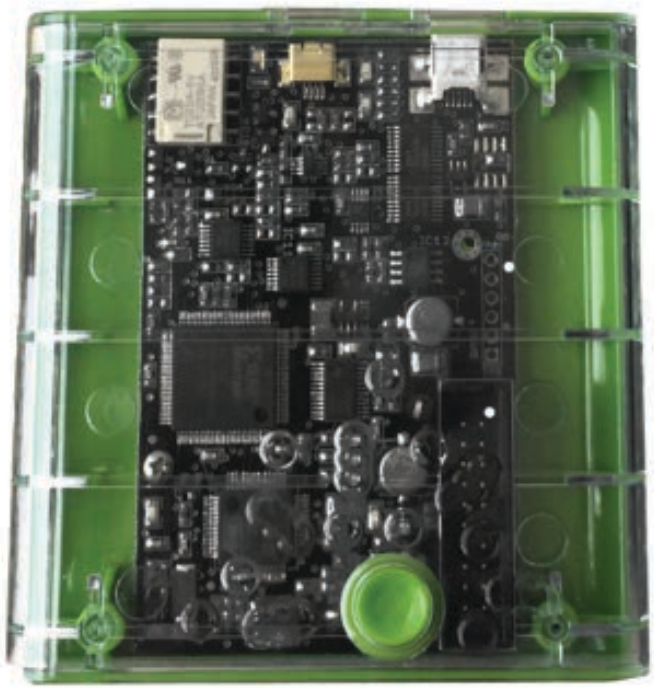
Three main immobilizer chips used (2012-13)

- TI's DST (**40**-bit key)
  - Bono et al. "Security Analysis of a Cryptographically-Enabled RFID Device" [Usenix Security'05]
- NXP's Hitag2 (**48**-bit key)
  - Analysed in our paper "Gone in 360 Seconds: Hijacking with Hitag2" [Usenix Security'12]
- EM's Megamos Crypto (**96**-bit key)
  - **This talk**

Megamos Crypto Usage (2013)

Make	Models
Alfa Romeo	147, 156, GT
Audi	A1, A2, A3, **A4 (2000)**, A6, **A8 (1998)**, Allroad, Cabrio, Coupe, Q7, S2, S3, S4, S6, S8, **TT (2000)**
Buick	Regal
Cadillac	CTS-V, SRX
Chevrolet	Aveo, Kalos, Matiz, Nubira, Spark, Evanda, Tacuma
Citroen	**Jumper (2008)**, Relay
Daewoo	Kalos, Lanos, Leganza, Matiz, Nubira, Tacuma
DAF	CF, LF, XF
Ferrari	California, 612 Schaglietti
Fiat	Albea, Doblo, Idea, Mille, Multipla, Palio, **Punto (2002)**, Seicento, Siena, **Stilo (2001)**, **Ducato (2004)**
Holden	Barina, Frontera
Honda	Accord, Civic, CR-V, FR-V, HR-V, Insight, **Jazz (2002, 2006)**, Legend, Logo, S2000, Shuttle, Stream
Isuzu	Rodeo
Iveco	Eurocargo, Daily
Kia	Carnival, Clarus, Pride, Shuma, Sportage
Lancia	Lybra, Musa, Thesis, Y
Maserati	Quattroporte
Opel	Frontera
Pontiac	G3
Porsche	911, 968, Boxster
Seat	Altea, Cordoba, **Ibiza (2014)**, Leon, Toledo
Skoda	**Fabia (2011)**, Felicia, Octavia, Roomster, Super, Yeti
Ssangyong	Korando, Musso, Rexton
Tagaz	Road Partner
Volkswagen	Amarok, Beetle, Bora, Caddy, Crafter, Cross Golf, Dasher, Eos, Fox, Gol, **Golf (2006, 2008)**, Individual, Jetta, Multivan, New Beetle, Parati, Polo, Quantum, Rabbit, Saveiro, Santana, **Scirocco (2011)**, Touran, **Tiguan (2010)**, Voyage, **Passat (1998, 2005)**, Transporter
Volvo	C30, **S40 (2005)**, S60, S80, **V50 (2005)**, V70, XC70, XC90, XC94

Hardware Setup



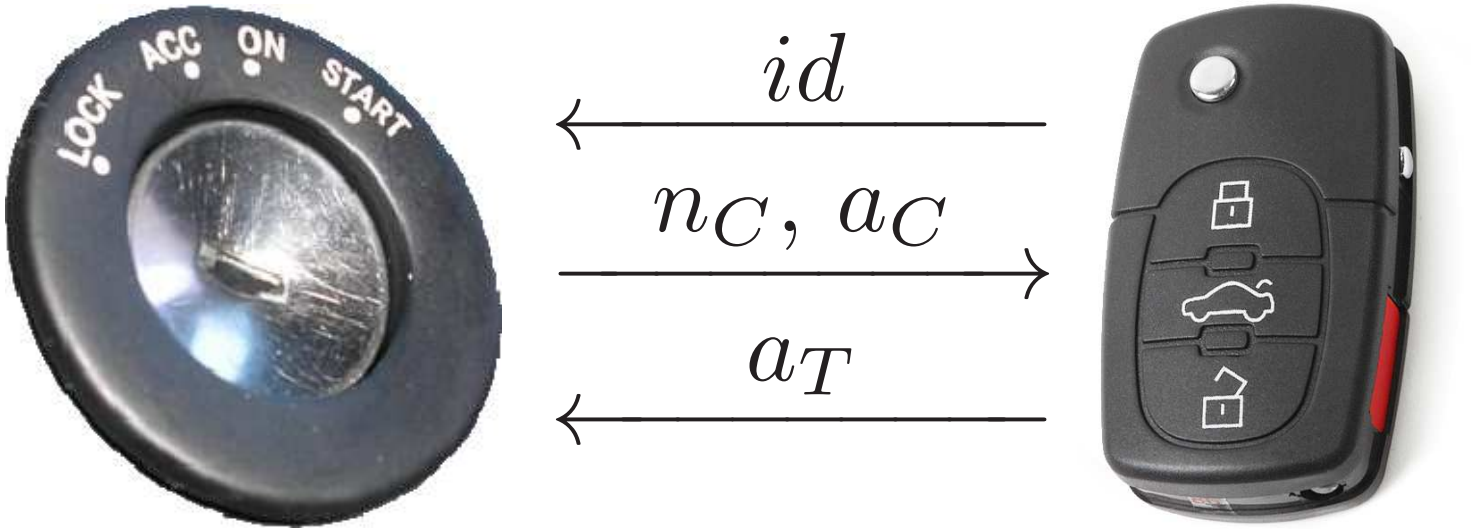
- Proxmark III
  - 125 kHz, 13.56 MHz
  - ADC, uC and FPGA
  - Open design/source

Tag Memory layout (from datasheet)

Block	Content	Denoted by
0	user memory	um_0 um_{15}
1	user memory, lock bits	um_{16} $um_{29} l_0 l_1$
2	device identi cation	id_0 id_{15}
3	device identi cation	id_{16} id_{31}
4	crypto key	k_0 k_{15}
5	crypto key	k_{16} k_{31}
6	crypto key	k_{32} k_{47}
7	crypto key	k_{48} k_{63}
8	crypto key	k_{64} k_{79}
9	crypto key	k_{80} k_{95}
10	pin code	pin_0 pin_{15}
11	pin code	pin_{16} pin_{31}
12	user memory	um_{30} um_{45}
13	user memory	um_{46} um_{61}
14	user memory	um_{62} um_{77}
15	user memory	um_{78} um_{93}

read-only
write-only
read-write

Megamos Authentication Protocol



id = 32-bit Tag identifier

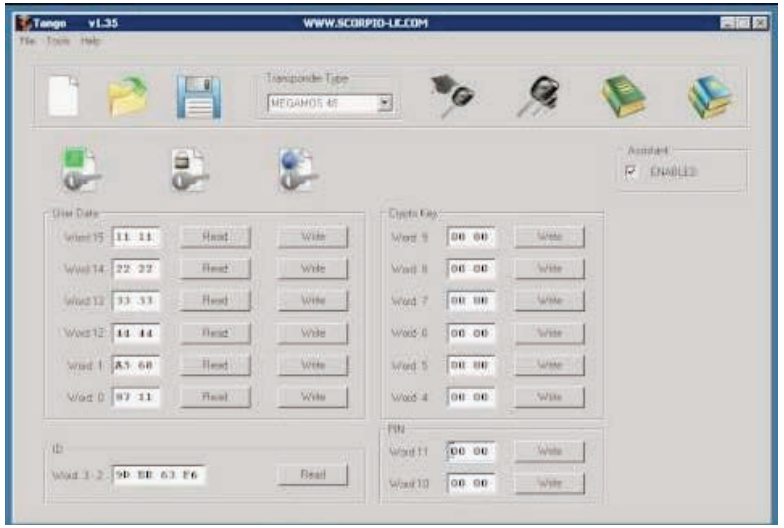
n_C = 56-bit Car nonce

a_C = 28-bit Car authenticator (keystream)

a_T = 20-bit Tag authenticator (keystream)

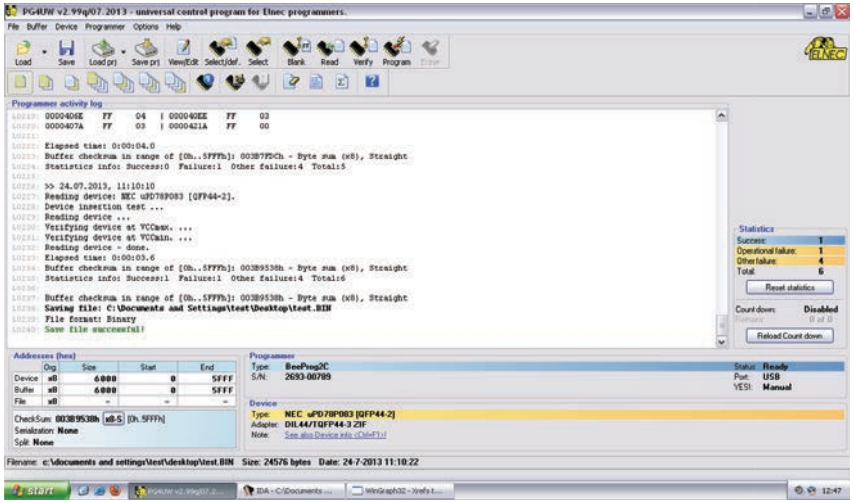
Reverse engineering Megamos Crypto

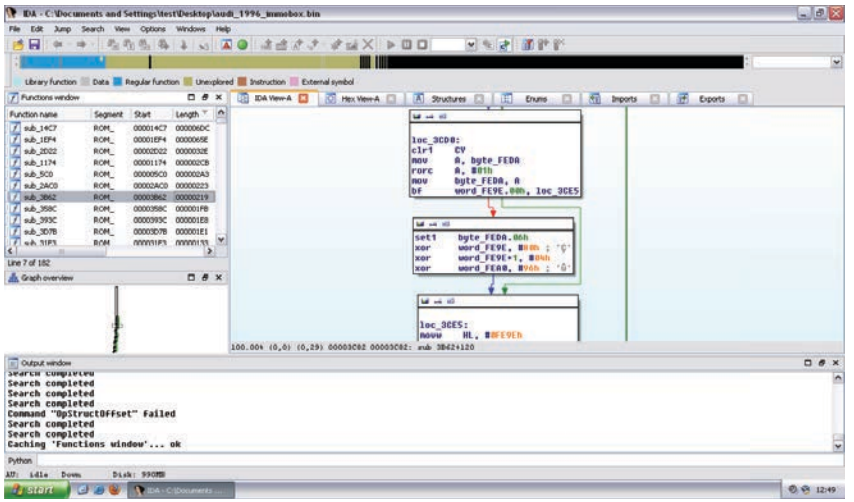
- We discovered that the Tango Programmer (car diagnostic tool) uses the Megamos Crypto algorithm since 2009 (for testing purposes only)
- We reverse-engineered the algorithm from the freely available Tango software package bypassing its obfuscation.



… but you can also read it directly from the car's ECU

NEC uPD78P083 has simply **no protection**





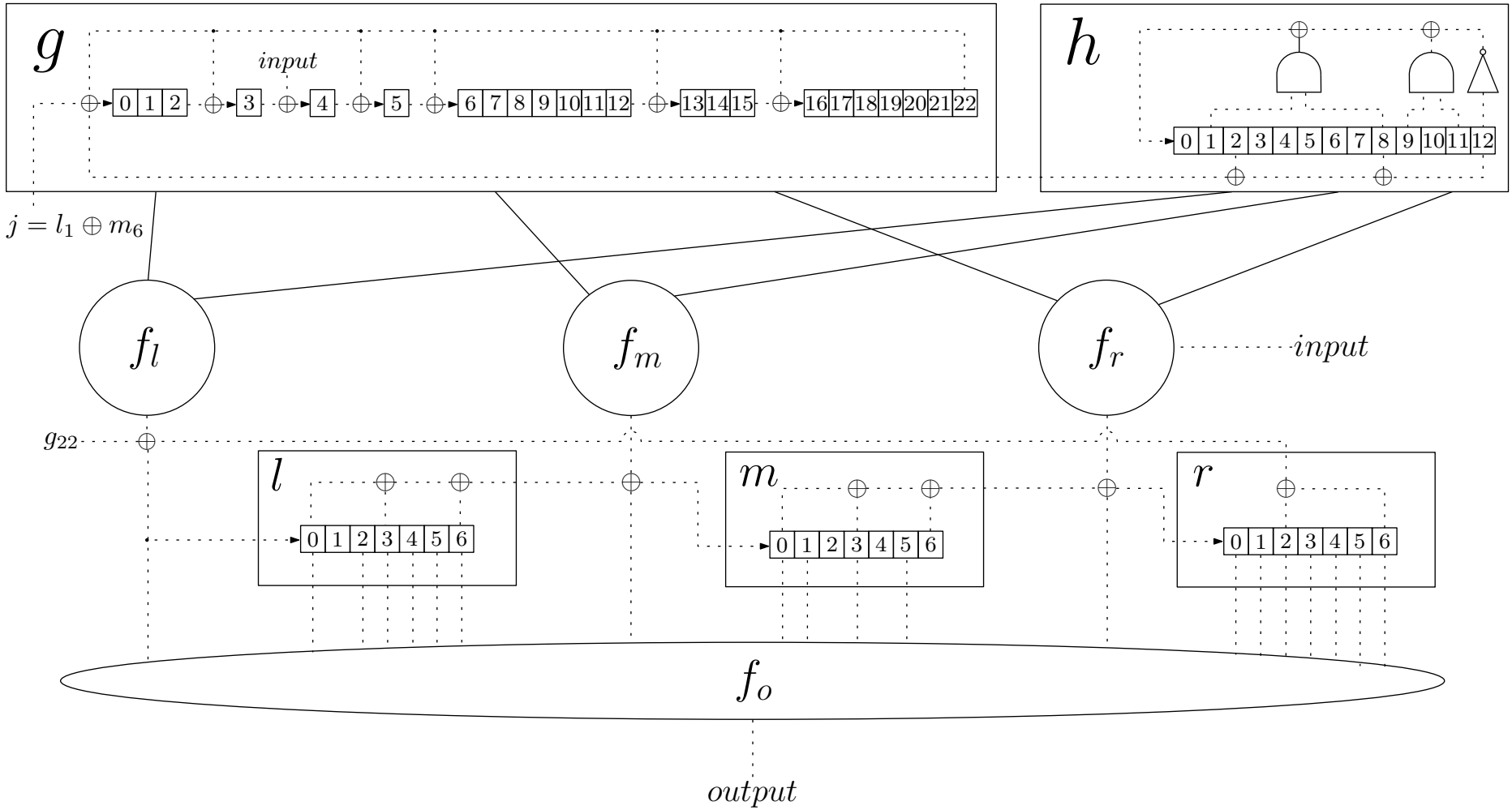
Cryptanalysis - Pre-requisites

- Requires access to the **car and the car key**
- Adversary needs to turn the ignition on twice and eavesdrop two traces

Origin	Message
Car	3
Transponder	A9 08 4D EC
Car	5
Transponder	80 00 95 13
Car	F
Transponder	AA AA AA AA AA AA AA AA
Car	6 | 3F FE 1F B6 CC 51 3F | 0^7 | F3 55 F1 A
Transponder	60 9D 6

Complexity analysis of the cipher

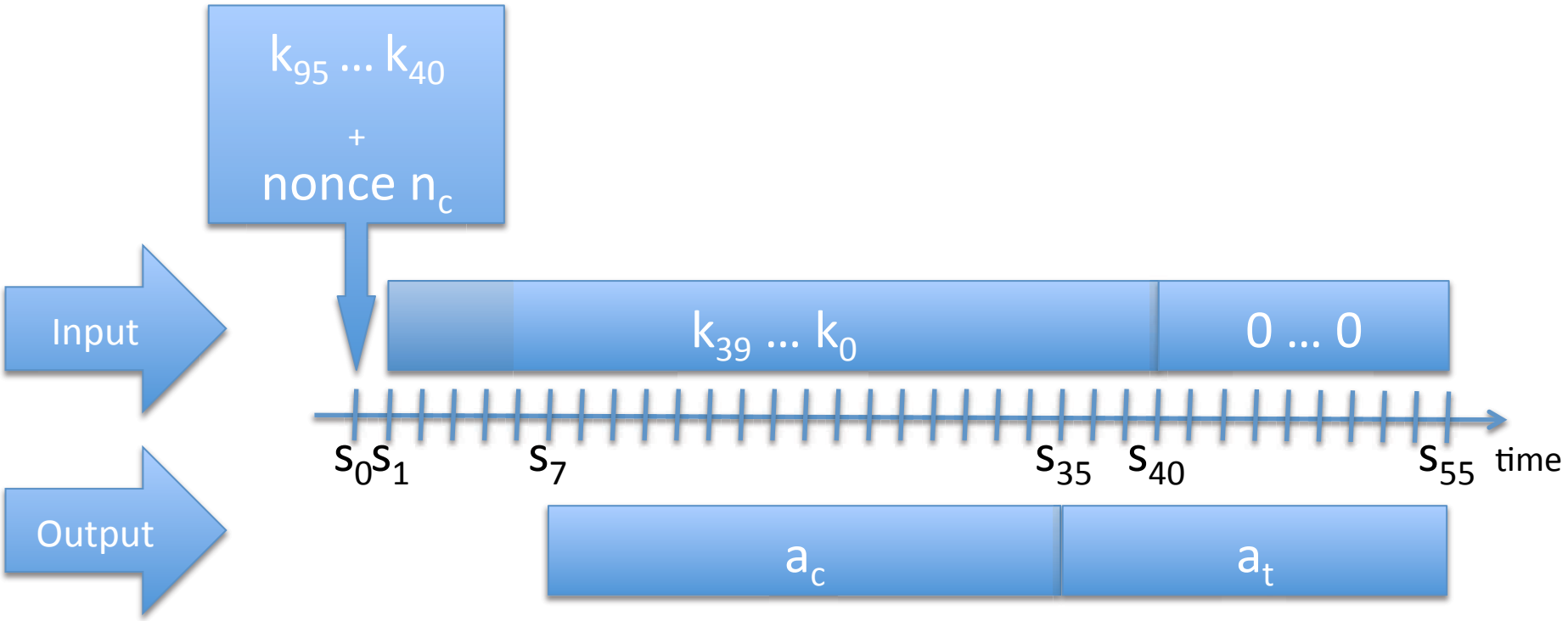
The Megamos Crypto Cipher



Secret key size = 96 bits

Internal state size = 23 + 13 + 3x7 = 57 bits

Megamos Crypto Initialization and workings



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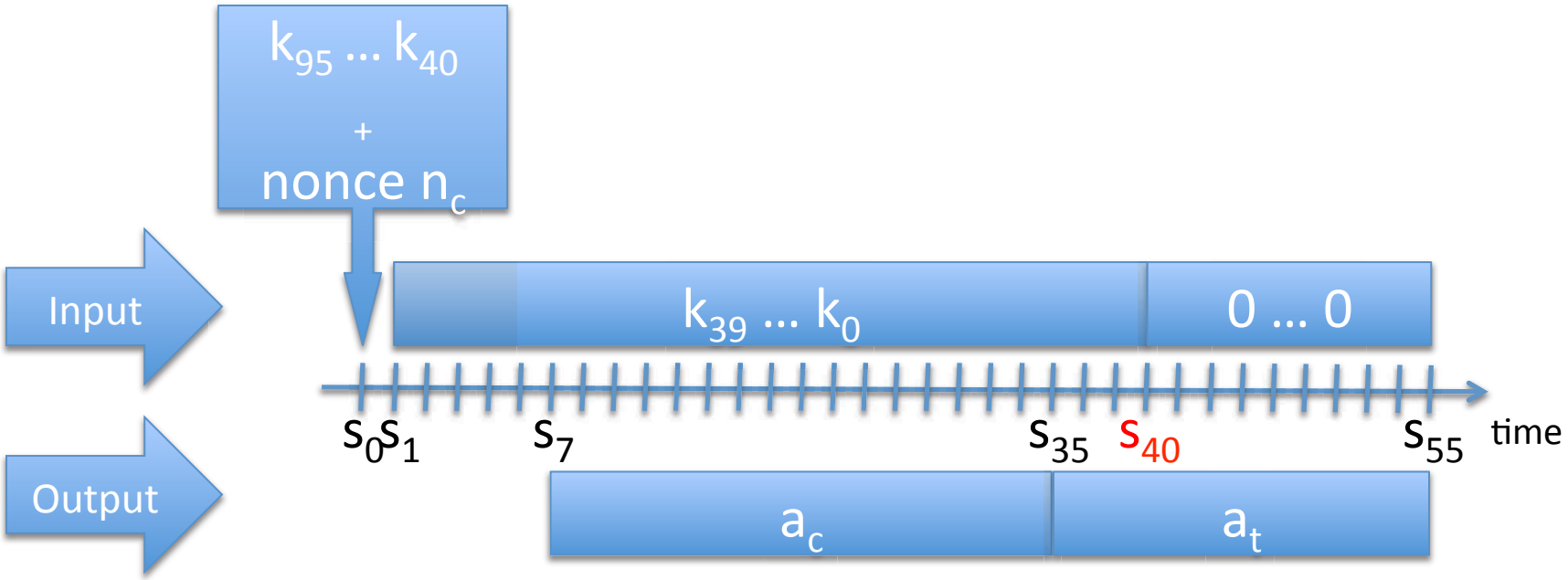
Cryptanalysis of Megamos Crypto



- Take the first authentication trace
- Trying all 2^{56} states $s_{40,}$ running 15 steps discarding on the output leaves 2^{41} candidate states
- After running the cipher backwards to s_7 we still have 2^{41} candidates
- Running backwards to s_0 guessing 7 bit leaves 2^{48} candidate keys.
- Check against a second authentication trace singles out the key.

Cryptanalysis of Megamos Crypto

- Total attack complexity reduced from 2^{96} to less than 2^{56} encryptions
- Takes less than two days on a Copacobana‘05
- This complexity can be further reduced by precomputation:
  - E.g., using a 12 Terabyte table reduces the complexity to 2^{49} table lookups
  - This has some practical limitations

Partial Key-update Attack

Observations:

During our research, the majority of deployed tags we found were:

- Unlocked $l_0 = 0$ (writable)
- Could be unlocked with a default PIN code

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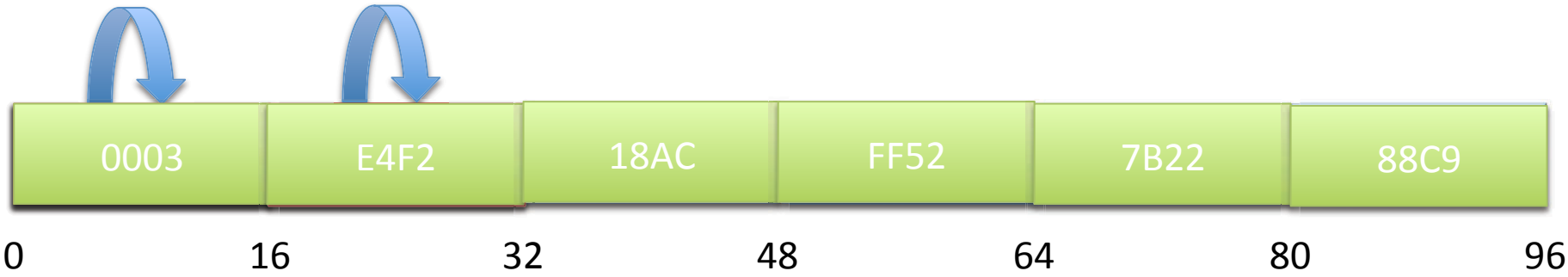
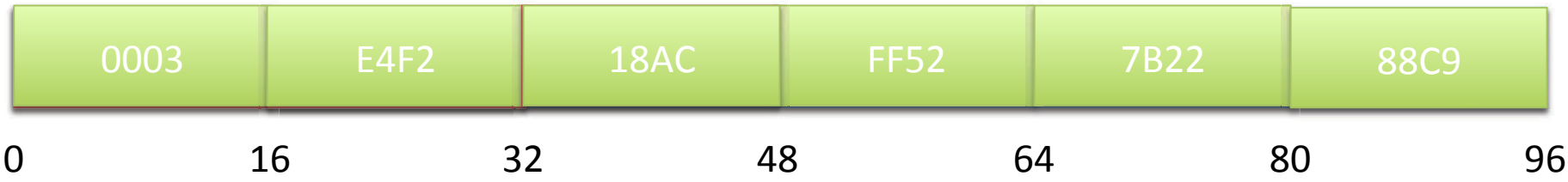
- The 96-bit secret key is written to the tag in blocks of 16 bits instead of being an atomic operation.

Partial Key-update Attack (simple)



- Get one authentication attempt from the car
- Guess 16 bits, write on one block then authenticate to the tag.
- If it succeeds you learn 16 key bits.
- This requires 6 x 2^{16} writes and authenticate
- Takes 25' per block ≈ 2.5 hours in total, using a Proxmark

Partial Key-update Attack (optimized)



- Same principle but only write zeros once in the first block
- Then increment the nonce and authenticate until the tag accepts
  - **Remember key is added to the nonce** during initialisation
- Repeat for another two blocks then combine with the cryptanalytic attack searching for the remaining bits
- This attack requires 6 writes and 3×2^{16} authentications with the tag and negligible computational complexity
- The whole attack takes <30 minutes using a Proxmark III

Immobilizer Demo

Weak key attack

Some interesting keys we found

- If the key starts with 32 zero bits then you can use a time-memory trade-off as in [Oechslin'03]
- Build (once) a 1.5 Terabyte rainbow table (less than one week to build)
- Computational complexity of 2^{37} encryptions
- Few minutes computation on a laptop

Weak key attack

Some even more interesting keys we found

Car	Secret key
A 1	00000000**d**8 **b**3**9**67c**5**a**3**c**3**b**2**9
A 2	00000000**d**9 **b**7**9**d7a**5**b**3**c**3**b**2**8
B 1	0000000**0**0 **0**0**0**1**0**4**0**5**0**5**0**9**0**5

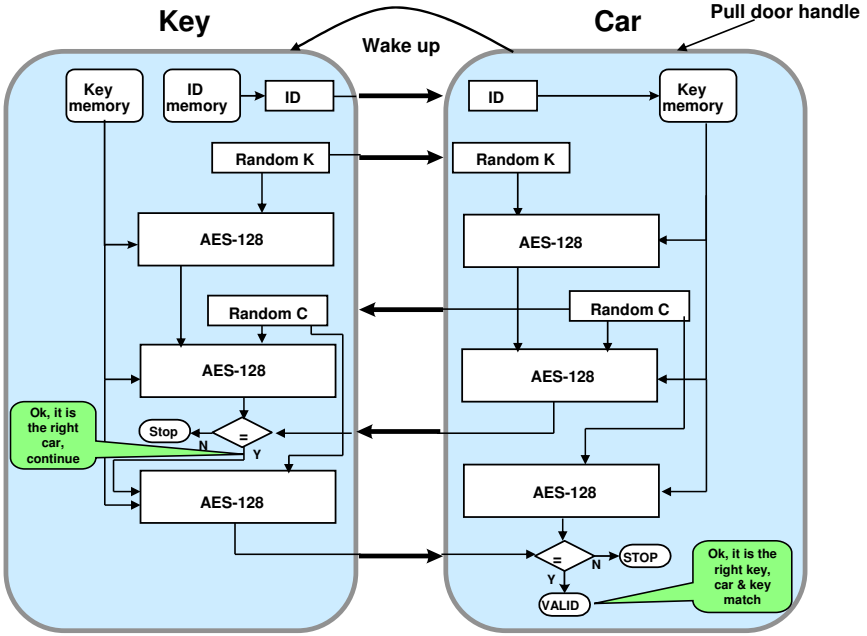
- These keys appear to have at most 32 bits of entropy
- An exhaustive search on such key takes only seconds

Mitigation and Alternatives

- Car owners can set lock-bit l_0 to one, set a random PIN. This prevents our partial key update attack.
- Set full entropy keys (locksmiths, dealers)
- Vehicle immobilizer tags based on the Advanced Encryption Standard (AES)
    - HITAG Pro, NXP Semiconductors (2007)
    - ATA5580, Atmel Corporation (2010)
    - TRPWS21/TRPBS27, Texas Instruments (2010)

Atmel Open Immobiliser Protocol Stack

- Atmel Corporation states in the datasheets:
  "Rather than developing its own proprietary cryptographic functions, Atmel selected and implemented the 128-bit AES-128 global benchmark standard as its data encryption and decryption source. ***This open source standard is freely available to the public for use and scrutiny****. Because of this it continues to be favored by industry experts over private and proprietary crypto algorithms."*
- Key Features
  - No security by obscurity
  - Use of 128-bits AES
  - Car & key send challenge
  - Open protocol design
  - Open source examples
  - Allows public evaluation



Responsible disclosure

- We carefully followed the official guidelines from the Dutch Government [1]
- We notified the chip manufacturer in November 2012, nine months ahead of scheduled publication at Usenix'13.
- We invested many days to inform them properly
  - conference call
  - several letters and emails
  - personal meeting
- We understand that measures have been taken to prevent our weak-key and partial key-update attacks in newer vehicles

[1] https://www.ncsc.nl/english/current-topics/responsible-disclosure-guideline.html

Thanks for staying around!

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