Investigating Profiled Side-Channel Attacks Against the DES Key Schedule

Johann Heyszl[1], Katja Miller[1], Florian Unterstein[1], Marc Schink[1], Alexander Wagner[1],
Horst Gieser[2],
Sven Freud[3], Tobias Damm[3], Dominik Klein[3], Dennis Kügler[3]

[1] Fraunhofer Institute for Applied and Integrated Security (AISEC)
[2] Fraunhofer Research Institution for Microsystems and Solid State Technologies (EMFT)
[3] Federal Office for Information Security (BSI)

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Motivation and Main Research Questions

- Several ePrint publications [WH17, WHG17, WH18] describe:
  - Successful profiled attack against DES key schedule of a commercial security controller
  - ‘Single trace attack’, ‘weak keys’, ‘remaining rest entropies as low as 19 bits’

- Important questions open/unanswered:
  - Wide distributions and SCA-weak keys reproducible using state of the art tooling?
  - Device-specific or more general - other devices?
  - Precise impact on 3-key triple-DES?
  - Predictable through simulation?

Empirical Study: Commercial Security Controller

- Security controller, Java-Card, programmable for investigation
- Target: DES key schedule

- High-precision EM setup. Decapped security controller. Backside.

- Alignement
- t-Test on preliminary leakage assumption: Leakage detected and measurement position selected
- Correlation-based leakage test CPOI [DS16]: POI selection

DES Key Schedule - Round Keys and Bit Transitions

Round key #	Indices refer to the input key excluding parity bits																						
0	8	44	29	52	42	14	28	49	1	**7**	16	36	2	30	22	21	38	50	51	0	31	23	15	35
1	1	37	22	45	35	7	21	42	51	**0**	9	29	52	23	15	**14**	31	43	44	50	49	16	8	28
2	44	23	8	31	21	50	7	28	37	43	52	15	38	9	1	**0**	42	29	30	36	35	2	51	**14**
3	30	9	51	42	7	36	50	**14**	23	29	38	1	49	52	44	43	28	15	16	22	21	45	37	**0**
4	16	52	37	28	50	22	36	**0**	9	15	49	44	35	38	30	29	**14**	1	2	8	7	31	23	43
5	2	38	23	**14**	36	8	22	43	52	1	35	30	21	49	16	15	**0**	44	45	51	50	42	9	29
6	45	49	9	**0**	22	51	8	29	38	44	21	16	7	35	2	1	43	30	31	37	36	28	52	15
7	31	35	52	43	8	37	51	15	49	30	**7**	2	50	21	45	44	29	16	42	23	22	14	38	1
8	49	28	45	36	1	30	44	8	42	23	**0**	52	43	**14**	38	37	22	9	35	16	15	7	31	51
9	35	**14**	31	22	44	16	30	51	28	9	43	38	29	**0**	49	23	8	52	21	2	1	50	42	37
10	21	**0**	42	8	30	2	16	37	**14**	52	29	49	15	43	35	9	51	38	7	45	44	36	28	23
11	7	43	28	51	16	45	2	23	**0**	38	15	35	1	29	21	52	37	49	50	31	30	22	**14**	9
12	50	29	**14**	37	2	31	45	9	43	49	1	21	44	15	7	38	23	35	36	42	16	8	**0**	52
13	36	15	**0**	23	45	42	31	52	29	35	44	7	30	1	50	49	9	21	22	28	2	51	43	38
14	22	1	43	9	31	28	42	38	15	21	30	50	16	44	36	35	52	**7**	8	14	45	37	29	49
15	15	51	36	2	49	21	35	31	8	14	23	43	9	37	29	28	45	**0**	1	7	38	30	22	42

- Key schedule, 56 bit keys, 16 rounds, half of round keys depicted (‘register C’)
- Round keys only permutations of initial key bits
- Bits re-occur, even subsequent bit-pairs re-occur

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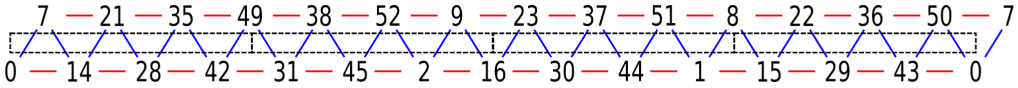
Leakage Model and Template Attack



- Key bits from register C. Transitions as dashes between bits. Coloring depicts occurrence rate (e.g. red 3 times, blue 10 times)
- Leakage model investigated precisely through SNR calculations: Exclusive XOR-leakage
  - XORs grouped and profiled in templates (instead of bits)
  - Dashed boxes mark grouped XORs for templates (4 in register C, 8 in total)
- Template attack: 7 bit templates, 2.5 mio profiling, 300 POIs, 1k attacked keys, 1/3/900 traces per key for attacker
- State of the art key rank estimation because independent XORs → security level in bits

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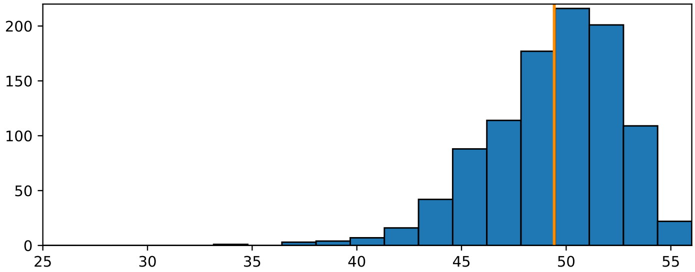
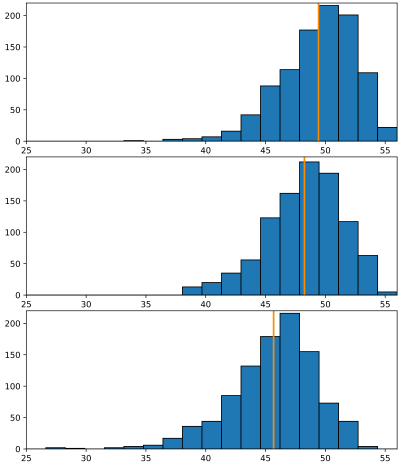
Single DES Results Show Wide Distribution

- Security level [bits] of 1k keys as histogram



- Reduction on average and widely distributed results with apparent weak keys (unlike usual DPA results)
- The limit is low (i.e. **2** bit for the all-zeros/all-ones keys). The more keys are tested, the more weak ones!

Single DES Results Show Wide Distribution



- Increasing the attack traces per key (to 3 and 900)
- Improvement for attacker
- Widely distributed even with high number of traces (while some noise factors are removed)

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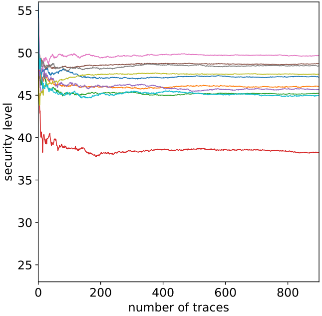
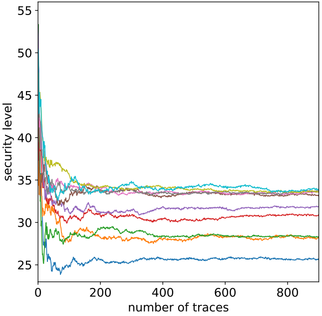
Key Weakness Asymptotically Independent of Noise but Value-Dependent





- Security levels over increasing traces per attacked key (left: 10 randomly selected, right: 10 low security level keys)
- Convergence to different levels - Key weaknesses inherent!
- Conclude that leakage model and switching noise determine key weakness

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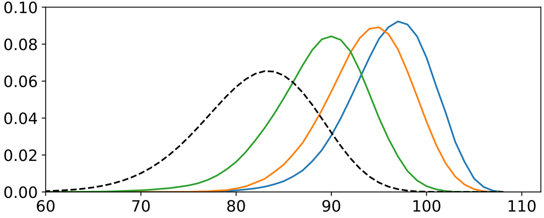
Overview and Comparison

	This work			Wagner et al.
	1k keys, 300 POIs			297k keys, 352 POIs
	1 trace	3 traces	900 traces	1 trace
	$1.5\times$DES per trace[1]			$4\times$DES per trace
Mean [bit]	**49.4**	**48.2**	45.7	**46.16** [WHG17, Fig. 11]

- Results similar, hence, reproducible
- What does this mean for actual applications - implications on triple-DES?

[1] 1 DES includes 9 backwards rounds, hence, $\approx$ **1.5** DES

Impact on 3-key triple-DES



- Estimate 3-key triple-DES security (allowing meet-in-the-middle advantage while using SCA results)
- Empirical density of security levels
- Based on previously shown independent single DES results (3 different keys):
  1 trace (blue), 3 traces (orange), 900 traces (green), noise-free simulation (black, dashed)

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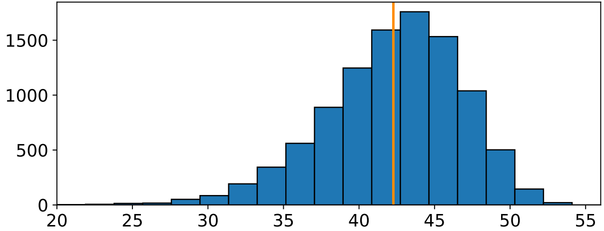
Impact on 3-key triple-DES

	1 trace	3 traces	900 traces	sim.
Mean sec. level 1-key 1-DES [bit]	**49.4**	**48.2**	**45.7**	**42.3**
Mean sec. level 3-key 3-DES [bit]	**96.1**	**93.8**	**88.7**	**82.1**
Fraction of 3-key 3-DES cases < **80** bit	**0.24** %	**0.43** %	**6.3** %	**37.4** %
Fraction of 3-key 3-DES cases < **70** bit	**0.0015** %	n.a.	**0.32** %	**4.0** %

- Security level for 3-key triple-DES high on average
- But small percentage of weak key-triples: E.g. **0.24** % < **80** bit after single trace attack - every 400th device

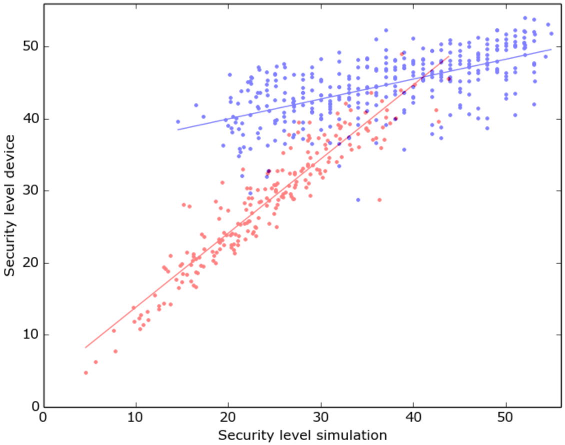
Generalisation through Simplified Simulation

- Simplified simulation: XOR leakage with equally weighted XOR-transitions
- No additional noise - only algorithm-dependent switching noise from key bits



- Wide distribution of security levels and weak keys even then! Issue must be more general

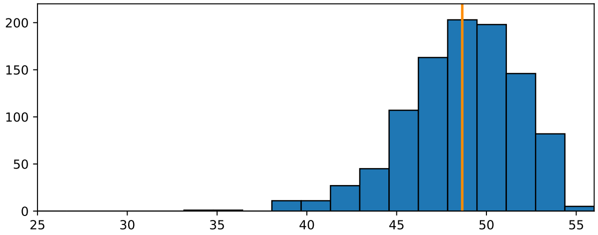
Simulation vs. Reality



- Security level attack results
- From simulated attack (x) and from actual measurements (y)
- Two classes: (blue) randomly selected, (red) random but ≈ 90% zeros/ones

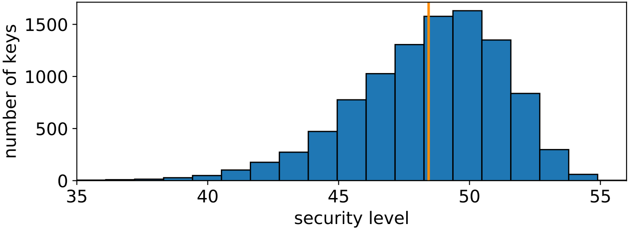
- Simulation prediction very precise for uneven zeros/ones, less for general keys
- Lack of precision likely due to simplified model w/o weighted XOR-transitions
- Key weakness not device-specific for big part

Empirical Study: Second Security Controller



- Similar results with mean security level of **48.7** bit (≈ **3** bit more)
- (460 POIs, 900 traces per key, 1000 keys)

Empirical Study: DES Engine in General Purpose µC



- STM32 HW DES engine
- Different leakage model: Exclusive value-based leakage
- Similar results! (100 traces per key, 10k attacked keys)
- Underlines generality of issue: Two different leakage models / implementations lead to widely distributed results!

Conclusion

- Wide distribution of security levels and weak keys exist
- Proven on different implementations/leakage models and in simulation
- More devices are affected if leakage from key schedule is existent (e.g. no effective masking)
- DES key schedule prone due to re-occurrence of transitions
- Impact on commercial security controller (3-DES) less dramatic than alleged (e.g. $\mathbf{0.24}\ \% < \mathbf{80}$)

- Open
  - How to assess security when results are widely distributed and weak keys exist?
  - Maybe similar with profiled attacks against other algorithms' key schedules if leakage is exploitable

Contact Information

Dr. Johann Heyszl

Hardware Security Department

Fraunhofer-Institute for Applied and Integrated Security (AISEC)

Address: Parkring 4
85748 Garching (near Munich)
Germany
Internet: http://www.aisec.fraunhofer.de

Phone: +49 89 3229986-121
E-Mail: johann.heyszl@aisec.fraunhofer.de

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Brute-force search strategies for single-trace and few - traces template attacks on the DES round keys of a recent smart card.
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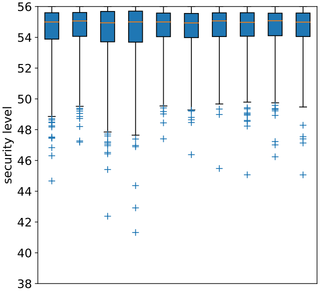
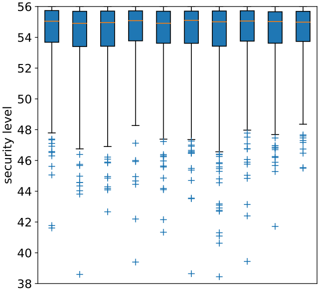
Impact of Noise Significant on Individual Traces





- When attacking the 900 traces as single trace attacks (same keys, left: 10 randomly selected, right: 10 low security level keys)
- Noise influence high on single traces - Even weak keys are often 'strong'
- (Previously shown distribution for single trace already include this noise of course.)

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