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Detecting Faults in Integer and Finite Field Arithmetic Operations for Cryptography

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Introduction

- Motivation and objectives
- Symmetric ciphers
  - Operations
- Error Detection
  - Error Detecting Codes
- Granularity of the code
- Frequency of checkpoints
- Results
- Conclusions and future research

Motivation (1/2)
Data Corruption

- Ciphers are developed to be resistant against linear and differential cryptanalysis
  - Similar plain texts must lead to completely different ciphered outputs
- Very few rounds are required to spread the difference over the whole block
- A single bit flip can alter half the block (i.e., the block is randomly correlated to the correct output)
  - Differences are fewer if error occurs at the end of the process (less rounds are computed afterwards)

Motivation (2/2)
Fault Attacks

- Fault attacks are a very efficient technique to break a cipher
  - Inject an error and collect information from the corrupted output
- Most attacks directed against AES, RSA
  - But also against DES and Elliptic Curves
- Actual application is the critical point
  - It requires physical access to the device and can be destructive; more difficult than power analysis
- EDCs can help detecting a fault attack!

Objectives

- Identify the common components of block ciphers and model the behavior in response to errors
- Associate EDCs to data block and develop a code prediction rule for (possibly) each operation
- Evaluate the suitability of a code to the whole cipher (i.e., overhead and error coverage)
- Explore the way from Error Detection to Fault Tolerance

Symmetric Ciphers

- Designed to be fast and efficient
- Process block of data (8,16 bytes)
- Different solutions exist
  - Each has its own properties (number of iterations, operations, ...): no major common characteristics
- Iterative structure simplifies design (even for detecting codes)
- Design based on *confusion* and *diffusion* principles
- We considered AES finalists together with Camellia, DES, IDEA and RC5

Operations

Ciphers	XOR	AND,OR	+, -	×	Sbox	Rot	Shift	Perm	× mod G(x)
Camellia	✓	✓			✓	✓		✓	
DES	✓				✓			✓	
IDEA	✓		✓					✓	
MARS	✓		✓	✓	✓	✓		✓	
RC5	✓		✓			✓			
RC6	✓		✓			✓		✓	
Rijndael	✓				✓			✓	✓
Serpent	✓				✓	✓	✓		
Twofish	✓		✓		✓	✓		✓	✓

- XOR: Every cipher
- AND, OR: Camellia only
- +: often used
  - -: in encryption, only MARS
- ×: slow and area-consuming
  - IDEA uses uncommon modulus
- Rotations: even data-dependent
- Shift: Serpent only
- Permutation: provides confusion
- Polynomial ×: Rijndael and TwoFish, over $GF(2^8)$
- S-Box: non-linear

Operations (1/3)

- eXclusive OR: the only operation used by all the ciphers (e.g., key mixing)
- Bit-wise AND and OR: logical operations, used only by Camellia
- Shifts and rotations: even data-dependent, they pose a challenge to hardware designers
  - Shift used only by Serpent: original input has to be forwarded anyway since shift is not invertible
- Permutations: easiest way to achieve confusion (input regularities are dispersed)

Operations (2/3)

- Modular arithmetic operations
  - Addition is often used
    - Subtraction is obviously used in decryption
    - Subtraction in encryption datapath is used only in MARS
  - Multiplication is used only in RC6, MARS and IDEA
    - It is a “complex” operation, relatively slow and area-consuming
    - Idea uses modulus (2^{16}+1), others use (2^{32})
- Polynomial multiplication over binary extension fields
  - used in Rijndael and Twofish

Operations (3/3)

- Substitution Box:
  - It is a replacement of bytes or words
  - It is often the main non-linear component; only IDEA and RC5/RC6 do not use it explicitly
  - It is usually implemented by means of a lookup table
    - it is usually byte-to-byte, in order to limit size
  - Sometimes it can be computed on-the-fly (AES), but more often its specification is a table itself
  - IDEA multiplication can be seen as a (very large) S-Box
    - (H. Raddum at Fast Software Encryption 2003)

Error Detection (1/2)

- First approach: duplication
  - Use two independent path and compare results
  - 100% hardware overhead, no additional latency
- Second approach: repeated computation
  - After the first computation, repeat the process and compare the results
  - It gives protection against temporary faults, not against permanent ones
  - No significant hardware overhead, but twice the latency
- These are generic solutions

Error Detection (2/2)

- Solutions specific to cryptographic device:
  - US patent 5432848: DES tables are extended to include error codes
- Exploit unused hardware (Karri et al.)
  - Use decryption datapath to validate encrypted output
  - It can be done at encryption level, round level or operation level
  - No significant hardware overhead, if the device already supports decryption
  - Latency is minimized checking at the operation level
- Exploit idle units (Karri et al.)
  - Use encryption functional units in idle state (RC6)
  - Decryption datapath is not required
  - Protection only against temporary faults

Error Detecting Codes

- High coverage with low-order errors
  - They often provide 100% coverage of single bit errors
- With high-order error, coverage depends on redundancy
  - Output code and data match randomly
- Hardware overhead smaller than duplication
  - They need a code *generator*, a *comparator* and *propagation units* implementing the prediction rules
- They work better when simple prediction rules are available for the **whole** encryption process
  - The code is generated at the beginning and it is validated at the end of the process
  - Checkpoint frequency can be increased for higher coverage

Parity Codes

- It can be computed at the byte or at the word level
  - It can be tuned from a single bit per word up to the desired redundancy level
- Parity of *n*-bit word is computed using *n-1* XOR ports
  - Simple computation
- It intrinsically fails on even-order faults (i.e., an even number of errors)
  - It can detect all odd-order faults, when frequent checkpoints are scheduled

Residue Codes

- It is computed taking the modulo (2^s-1)
  - s is the number of check bits
  - It can be computed through a weighted sum of the word bits
- Unlike parity, it does not allow using a single check bit
  - Minimum redundancy is 2 bits (residue base 3)
  - It is usually computed at the word level, to minimize overhead
- Coverage is similar for even-order and odd-order faults

Matching EDCs to Operations (1/3)

- Parity is more suited to logical operations; the prediction rules are...
  - eXclusive OR: ...the XOR of the input parities
  - Rotation: ...parity is unchanged, if the code is at the same level of the operation
  - Shifting: ...must consider bits leaving and entering the word
  - Polynomial multiplication: ...if defined over GF(2^n), it is easily predictable when one of the operands is known a priori
  - Data-dependent operations (RC5, RC6) are obviously more complex
- Addition and multiplication must consider **all** the carries that are required to compute the result

Matching EDCs to Operations (2/3)

- Residues are more suited to arithmetic operations; the prediction rules are...
  - Addition: ...the sum of the input residues
    - but overflow needs correction!
  - Multiplication: ...the product of the input residues
    - but most significant (and neglected) bits need a corrective term
  - Shifting: ...it can be seen as a multiplication by a power of 2
  - eXclusive OR: ...the sum of the input residues, but a correction term is needed
- Prediction of the code after polynomial multiplication over GF(2^n) is expensive

Matching EDCs to Operations (3/3)

- Some operations are not suited to parity codes:
  - Logical AND and OR: prediction is much more expensive than duplication
  - Validate the code, protect by duplication and generate the code from scratch
- Some operations are suited both to residue and parity:
  - Substitution boxes: the output code is stored together with the result; the input code is used for implicit validation
  - Address protection by concatenating check bits introduces a large overhead (1 additional bit doubles the table size)
    - Use custom address decoding unit to reduce the area overhead

Cost of Prediction Rules

Operation	Parity Cost	Residue Cost
XOR	Yes	Yes
AND, OR	More expensive than duplication	
Integer +, -	Yes	Yes
Integer Mult.	Expensive	Yes
Substitution Box	Yes	Expensive
Rotation	Yes	Yes
Shift	Yes	Yes
Permutation	Yes	Yes
Polynomial Mult.	Yes	Expensive

EDC Granularity

- Symmetric ciphers operate on different word size (8, 16, 32 bits)
- Code granularity should not be larger than operand size
  - The code should be validated and regenerated with each operation! (e.g., substitution tables)
- Finer code adds further complexity and overhead
  - Detection rate improves
  - Prediction rule may become more complex

Choosing the Proper EDC

Cipher	Suggested Code
Camellia	Intractable by EDC
DES	Parity
IDEA	Residue, but expensive
MARS	Residue, but expensive
RC5	Parity or residue
RC6	Residue
Rijndael (AES)	Parity, per byte
Serpent	Parity, per byte
Twofish	Parity, per byte

Choosing the Proper EDC (1/3)

- If operations do not allow affordable code prediction, prefer **duplication** of functional unit
  - (Camellia and logical operations AND and OR)
- If cipher uses multiplication, then use **residue** (RC6)
- If cipher uses polynomial multiplication, then use **parity** (AES, Twofish)

Choosing the Proper EDC (2/3)

- Some ciphers use operations suitable for different codes:
  - MARS uses substitution boxes (⇨parity) and integer multiplication (⇨residue)
  - RC5 uses addition, rotations, XORs
- Using residue codes is the only (expensive) choice
  - MARS: use **residue**, but validate before S-Box
  - RC5: both **parity** code and **residue** are affordable; the choice can be done according to the desired coverage/overhead ratio

Choosing the Proper EDC (3/3)

- IDEA uses multiplication
  - Use residue codes
  - The modulus is uncommon
    - The computation of the correction term (due to discarded bits) is complex and expensive
  - Use **residues**, but insert checkpoints before products
- DES is based on lookup tables
  - Expansion and S-Box work on small nibbles
    - Residue has excessive overhead
  - Round permutation does not alter word-level parity
    - Simple, but poor coverage
  - Use **parity** (per byte), but frequent checkpoints are required

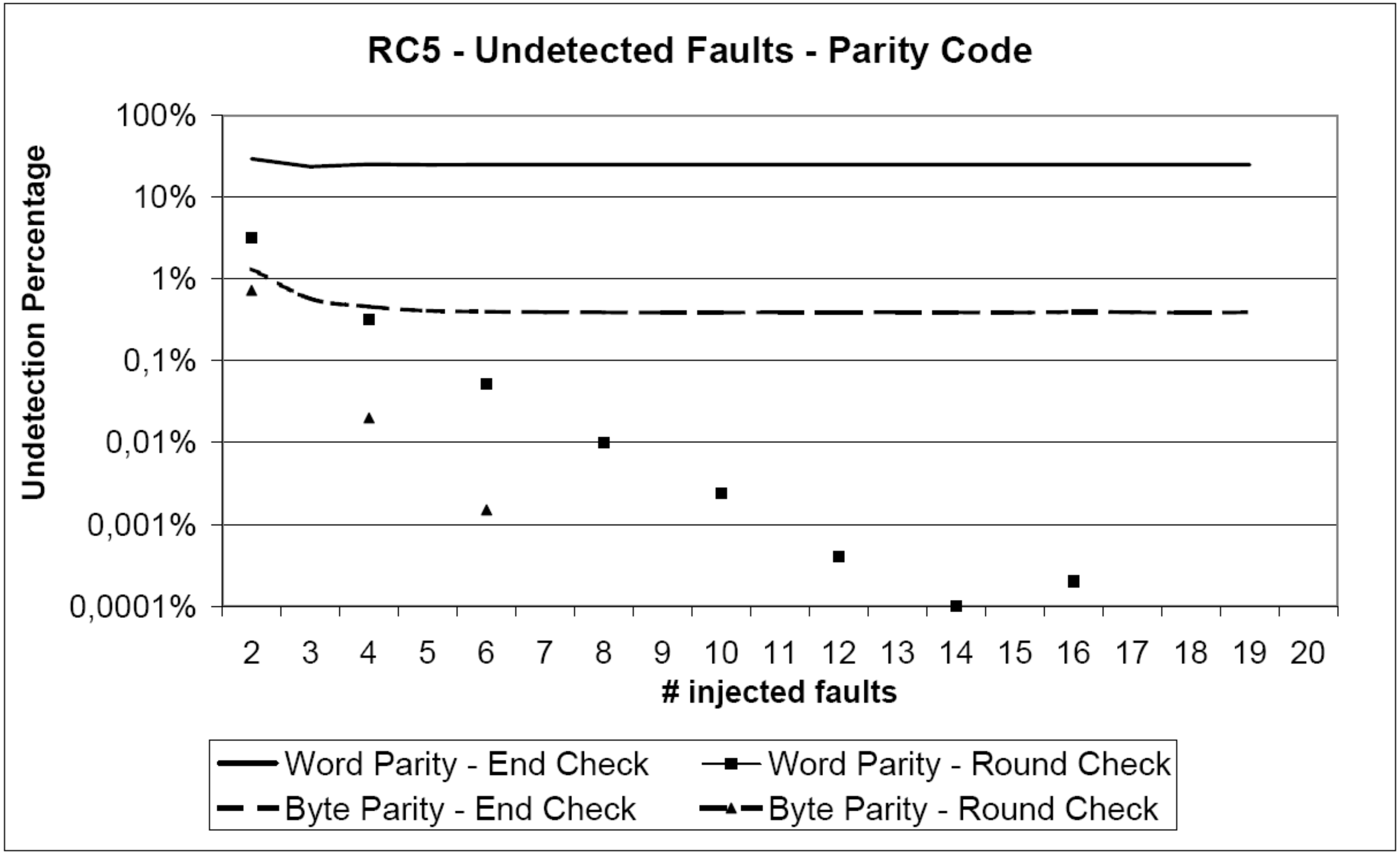
Frequency of Checking (1/2)

- There are three main levels:
  - After whole encryption, at the end of some rounds, after inner operations
- With higher checkpoint frequency, the detection latency is lower
  - But critical path is longer, hence lower clock rate can be achieved
- Frequency affects also detection coverage
  - Error masking can be avoided by frequent checkpoints
  - Frequent checkpoints may increase the false positives
- Checkpoint must be scheduled *before* any error is completely masked by encryption process

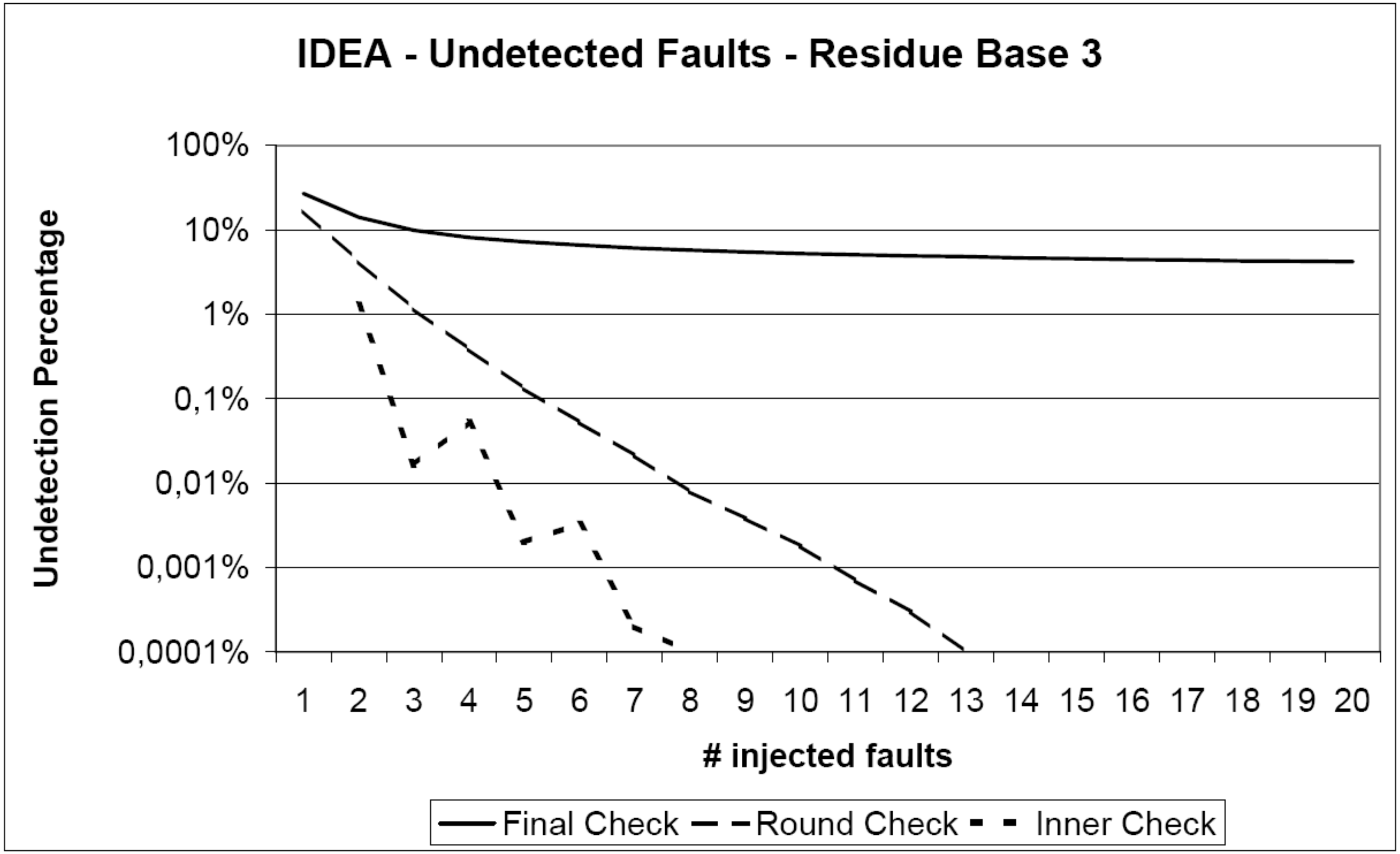
Frequency of Checking (2/2)

- Single-fault model:
  - Any difference between the predicted and the actual code allows detecting the error
  - After fault injection, each round makes the error evolve by spreading and cancelling the differences
  - If the error is completely cancelled, the fault will not be detected
    - If a premature cancellation may occur, a checkpoint MUST be scheduled
  - AES and RC5 models allow the single fault to reach the end of encryption
    - Single fault is always detected
  - IDEA simulations have shown that error cancellation can occur even for single faults

Coverage – Parity Code



Coverage – Residue Code



Conclusions

- Error detecting codes are a reasonable alternative to duplication:
  - Reduced hardware overhead
  - Parity and residue codes cover a wide range of cryptographic operations
  - Many degrees of freedom allow to choose the desired coverage/cost tradeoff
    - Type of code
    - Granularity
    - Frequency of checkpoints
  - Optimum detection rate
    - Often 100% of single errors are detected
    - Detection rate depends on the number of check bits, when multiple errors are injected

Future Research

- Develop a library of cryptographic functional units with support to error detection
- Evaluate accurate hardware and latency overhead, depending on code and checkpoint frequency
- Develop fault *tolerant* atchitectures
  - AES model allows for fault location at the byte level
- Exploit error detection as a countermeasure against fault attacks
  - Recompute the result and output only correct data
  - Stop the device/erase key memory when an attack is detected