Secured Embedded Architecture Laboratory (SEAL)

Parsimonious Design Strategy for Linear Layers with High Diffusion in Block Ciphers

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INTRODUCTION

Linear Layers in Block Ciphers

Necessary Building Blocks

- Linear layers are crucial building blocks in the design of block ciphers

Security and Efficiency

- Provide the much needed diffusion
- Ensure low implementation costs

Systematic Design Techniques

- Limited work on generic construction techniques
- Need to combine both efficiency and security requirements

Objectives

A New Design Technique

- A hierarchical design technique for lightweight linear layers
- Technique applies to SPN block ciphers such as AES, PRESENT and PRIDE

Practical Demonstration of Proposed Technique

- Case Study on PRIDE
- Alternative linear layer designed using our new technique

Notion of Lightweightness

- Standard metric for testing lightweightness of any design is the ***area footprint on chip***
  - In ASIC based implementations, the aim is to reduce the Gate Equivalent of the design
  - On FPGA, the number of LUTs (look up tables) is minimized
- Ensure that the design functions at low frequency (usually around 100KHz) with less energy consumption
- Ensure optimal area-throughput product of the design

A POSSIBLE DESIGN TECHNIQUE

MDS Matrices for Linear Layers

- MDS matrices are suitable for linear layers due to their good diffusion properties.
- Must have a minimum number of ones in each row and each column to achieve desirable diffusion
- However, MDS matrices are not inherently lightweight by construction

Combining Lightweightness with MDS Properties

- Choose MDS matrices with lightweight roots that have less hardware requirements
- Implement these lightweight roots in hardware
- Iterate them to obtain the necessary diffusion properties
- Example : PHOTON linear layer

Challenges: Not Too Generic!!!

- The space for MDS matrices is too large
- For 32x32 binary MDS matrices with adequate diffusion levels, the space is almost as large as 2^{896}!!
  - Too large to search for MDS matrices with lightweight roots

OUR PROPOSED DESIGN TECHNIQUE

An Alternative Approach

- Start from lightweight matrices *A* of the form

$$A = \begin{pmatrix} 0 & 1 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & 1 \\ Z_1 & Z_2 & Z_3 & Z_4 & \cdots & Z_m \end{pmatrix}$$

or

$$A = \begin{pmatrix} Z_1 & Z_2 & Z_3 & Z_4 & \cdots & Z_m \\ 1 & 0 & 0 & 0 & \cdots & 0 \\ 0 & 1 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 1 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 1 & 0 \end{pmatrix}$$

An Alternative Approach (contd.)

- Iterate the underlying as many times as required to arrive at desired MDS matrix
- Search space for optimal choice much smaller : **reduced to the last row only**
- Can still be large for large dimension matrices

Divide and Conquer : Block Interleaving

- Construct the larger linear layer L from smaller linear layers $L_1, L_2,\ldots.L_k$

$$L = \begin{pmatrix} L_1 & \varnothing & \varnothing & \varnothing & \cdots & \varnothing \\ \varnothing & L_2 & \varnothing & \varnothing & \cdots & \varnothing \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \varnothing & \varnothing & \varnothing & \varnothing & \cdots & L_k \end{pmatrix}$$

- Ensure the smaller layers are optimally constructed from underlying lightweight matrices
- The diffusion of the smaller layers *guarantees diffusion for the larger linear layer* L

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AN ILLUSTRATION OF THE PROPOSED TECHNIQUE

- **Aim** : Construct 4 x 4 MDS matrix L over $GF(2^8)$ with target differential and linear branch number 5

- **Step-1** : Choose the underlying smaller lightweight matrices optimally via exhaustive search

$$A_{1,2^8} = \begin{pmatrix} 0 & 1 \\ 1 & 3 \end{pmatrix} \quad A_{2,2^8} = \begin{pmatrix} 3 & 1 \\ 1 & 0 \end{pmatrix}$$

- **Step-2** : Iterate 4 times to arrive at the desired smaller MDS matrices

$$L_{1,2^8} = \begin{pmatrix} 4 & 15 \\ 15 & 21 \end{pmatrix} \quad L_{2,2^8} = \begin{pmatrix} 21 & 15 \\ 15 & 4 \end{pmatrix}$$

- Combine to form the final linear layer

$$L_{2^8} = \begin{pmatrix} 4 & 15 & 0 & 0 \\ 15 & 21 & 0 & 0 \\ 0 & 0 & 21 & 15 \\ 0 & 0 & 15 & 4 \end{pmatrix}$$

- Comparison with PRIDE matrix : our matrix has 20% better diffusion properties with only 10% increase in area overhead

Comparison With Other Approaches

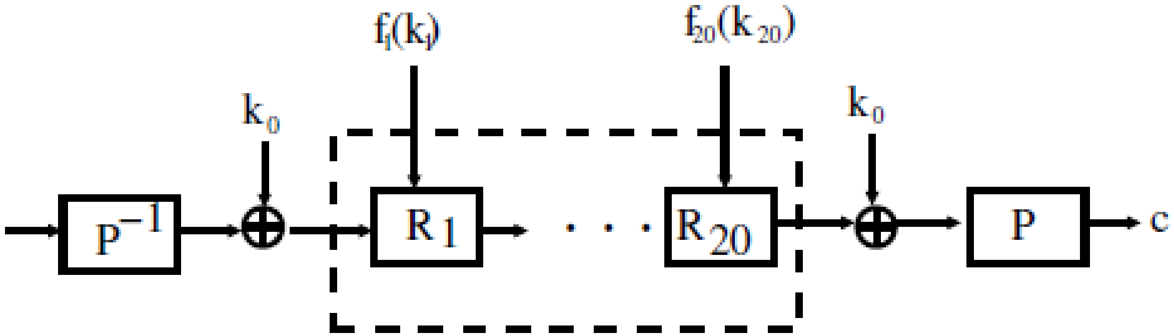
- For PRIDE like linear layer constructions, block interleaving is not used and search space for underlying matrices is 2^{16} times larger than in our construction

- Thus our proposed methodology yields cipher linear layers with similar area footprint, and good diffusion properties, while also reducing the computational complexity of the construction process.

CASE STUDY: PRIDE REVISITED

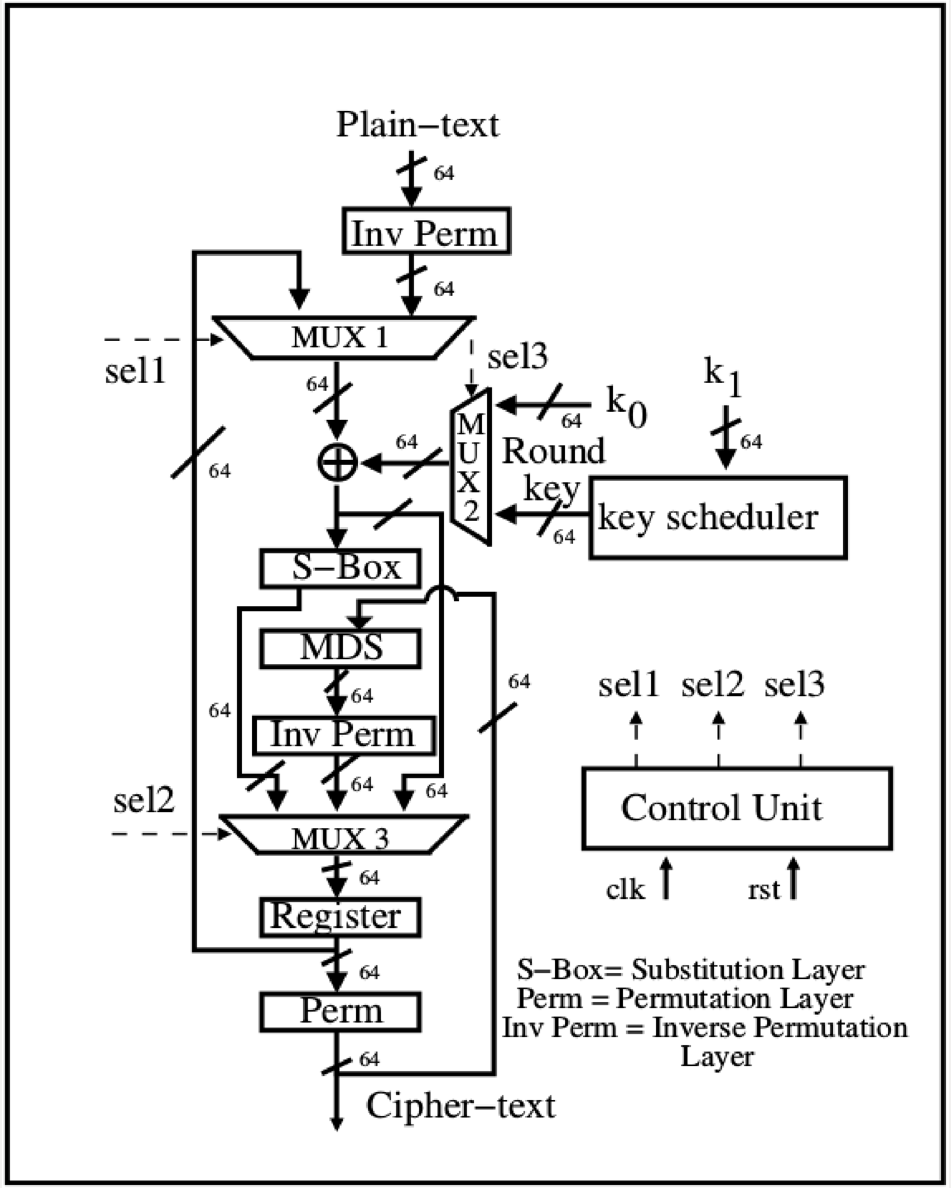
Case Study : PRIDE Revisited

We substitute the original linear layer of PRIDE with a linear layer constructed using our proposed technique. The interleaving construction is used, with each sub-matrix populated using $GF(2^8)$ elements that are chosen according to our proposed strategy



The Structure for PRIDE

PRIDE Redesigned : Lightweight Linear Layer



Results : PRIDE Redesigned

Strong Diffusion Layer

- 20% more diffusion than original
- Comparable security against linear and differential cryptanalysis

Lightweight PRIDE Construction

- 60% CMOS Gate Savings
- 50% LUT savings on FPGA
- Ideal for hardware oriented applications

Area Savings on Hardware – ASIC and FPGA results

Design Platform	Original PRIDE	Modified PRIDE	Percent Savings
ASIC	128 2-input XORs	50 2-input XORs	60
FPGA (expected)	64 LUTs	28 LUTs	56
FPGA (actual)	64 LUTs	32 LUTs	50

Conclusions

- We have proposed a generic construction strategy for linear layers in block ciphers which, to the best of our knowledge, is not yet very well studied in literature
- The focus is on minimizing the area footprint of block ciphers in the context of lightweight cryptography
- Our hierarchical construction provides a simple yet elegant technique of guaranteeing good diffusion properties while ensuring low hardware costs
- The technique has been validated via applications to the recently proposed block cipher PRIDE


THANK YOU
ANY QUESTIONS