Triathlon of Lightweight Block Ciphers for the Internet of Things

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Abstract. In this paper we introduce an open framework for the benchmarking of lightweight block ciphers on a multitude of embedded platforms. Our framework is able to evaluate execution time, RAM footprint, as well as (binary) code size, and allows a user to define a custom "figure of merit" according to which all evaluated candidates can be ranked. We used the framework to benchmark various implementation of 13 lightweight ciphers, namely AES, Fantomas, HIGHT, LBlock, LED, Piccolo, PRESENT, PRINCE, RC5, Robin, Simon, Speck, and TWINE, on three different platforms: 8-bit ATmega, 16-bit MSP430, and 32-bit ARM. Our results give new insights to the question of how well these ciphers are suited to secure the Internet of Things (IoT). The benchmarking framework provides cipher designers with a tool to compare new algorithms with the state-of-the-art and allows standardization bodies to conduct a fair and comprehensive evaluation of a large number of candidates.

Keywords: lightweight, block cipher, evaluation framework, IoT, usage scenario, AVR, MSP, ARM

1 Introduction

The Internet of Things (IoT) is a frequently-used term to describe the currently ongoing evolution of the Internet into a network of smart objects ("things") that have the ability to communicate with each other and with centralized resources via the IPv6 (resp. 6LoWPAN) protocol [1]. Today, the two most important and widely noticed exponents of the IoT are RFID technology (which has become a key enabler of modern supply-chain management and industrial logistics) and Wireless Sensor Networks (WSNs), which have found widespread adoption in several application domains ranging from home automation over environmental surveillance and traffic control to medical monitoring. A recent white paper by Cisco estimates no less than 50 billion devices being connected to the Internet by the year 2020 [2], which implies that, in the near future, every person in the industrialized world will be surrounded by hundreds of sensors, actuators, RFID tags, and many other kinds of smart objects yet to be developed. This evolution from the Internet of people to the Internet of Things will have a profound impact on our daily life and change the way we interact with the physical world surrounding us [1]. However, it is also evident that 50 billion smart devices connected to the Internet introduce unprecedented challenges to the security and privacy of their owners or users.

It is widely accepted that symmetric-key cryptosystems play a major role in the security arena of the IoT, but they need to be designed and implemented efficiently enough so as to comply with the scarce resources of typical IoT devices. Gligor defined in [3] lightweight cryptography as *cryptographic primitives, schemes and protocols tailored to extremely constrained environments such as sensor nodes or RFID tags*. A typical sensor node (e.g. the MICAz mote) is equipped with an 8-bit micro-controller (e.g. the ATmega128) clocked at 7.8 MHz and features 4 kB of RAM. Passive RFID tags do not even have a (software-programmable) processor, which means that performing cryptography on such tags is only possible through hardware implementation. It is often stated that security features on a low-cost tag may occupy no more than 2,000 Gate Equivalents (GEs). The efficient implementation of cryptographic primitives so that they are applicable in the highly constrained regimes of sensor nodes and RFID tags is a challenging task since, for example, performance is conflicting with other metrics of interest such as silicon area and power consumption (when thinking of hardware implementation) or memory footprint and code size (when implementing in software). In addition, lightweight primitives should withstand all

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known forms of cryptanalytic attacks (e.g. linear and differential cryptanalysis in the context of secret-key primitives) since lightweight cryptography is not meant to be "weak" cryptography, i.e. a lightweight cryptographic primitive should not be the weakest link in the security of a system [3].

In this paper we present a survey of lightweight block ciphers along with software benchmarking results we obtained on 8, 16, and 32-bit processors. We consider three metrics of interest: execution time, run-time memory (i.e. RAM) requirements, and binary code size. To ensure a fair and consistent evaluation, we developed a benchmarking toolsuite that we plan to make available to the cryptographic research community following the spirit of the well-known and widely-used eBACS [4] system. Our benchmarking tool is "open" in various aspects; first, it will be possible to upload new ciphers so that the designers get consistent and detailed feedback on how their cipher compares with the state-of-the-art. Second, the tool was developed from the ground up with the goal of supporting a wide range of embedded platforms through both cycle-accurate instruction set simulation and actual measurements on prototyping boards. Currently, our tool includes cycle-accurate instruction set simulators for AVR ATmega and TI MSP430, as well as an ARM development board equipped with a Cortex M processor. We use GCC for all platforms, but other compilers could be supported as well. Third, our tool is also open with respect to the evaluation metrics. Currently, it can evaluate execution time, RAM footprint, and binary code size. Other metrics can be derived thereof; for example, the energy consumption of a block cipher is simply the product of its running time and the average power consumption of the executing processor.

We report detailed benchmarking results for a total of 13 lightweight block ciphers, namely AES, Fantomas, HIGHT, LBlock, LED, Piccolo, PRESENT, PRINCE, RC5, Robin, Simon, Speck, and TWINE. Our rationale behind selecting exactly the mentioned 13 ciphers is twofold; first, each of these candidates has a special property or feature that makes it interesting for IoT applications. Second, they cover a wide range of different design strategies and approaches. Our evaluation considers two applications scenarios or use cases; the first considers the encryption of messages transmitted in a Wireless Sensor Network (WSN) and the second is a simple challenge-response authentication protocol with applications in smart cards. To accommodate the different requirements of these application scenarios, we implemented at least two versions of most of the 13 ciphers, a memory-optimized variant and a speed-optimized variant. The former can be seen as a minimalist implementation that favors low memory footprint and small code size over performance. On the other hand, the second implementation incorporates certain optimizations that increase code size and/or memory footprint (e.g. partial loop unrolling, use of small look-up tables) with the goal of improving performance.

All our implementations are written in C language to ensure portability across a wide range of 8, 16, and 32-bit platforms. This is important since there is no single dominating hardware platform in the IoT (in contrast to the "conventional" Internet of commodity computers, where the Intel architecture has a market share of over 90%). In other words, the IoT is populated by billions of heterogenous devices with largely incompatible processors and operating systems. Supporting all these processors through optimized assembly code is cumbersome since, for each processor architecture, a separate code base needs to be written, tested, debugged, and maintained. In the light of ever-increasing time-to-market pressure, many designers value the portability of C code higher than the performance of assembly code[1]. Therefore, the benchmarks we report in this paper are practically relevant, even though our C implementations do not achieve record-setting execution times. We put a similar effort into optimizing the implementations of all ciphers to ensure a consistent and fair evaluation. As mentioned before, supporting a large number of platforms through hand-optimized code would introduce significant overhead for a relatively little gain.

The performance evaluation of the lightweight block ciphers is an important aspect that should not be not neglected. As previous standardisation competitions for AES [5] and SHA-3 [6] showed, performance plays an important role in selecting future standards. Our work comes in a moment when NIST is considering to standardise lightweight primitives [7].

1.1 Related Work

Several similar projects evaluated the performance of lightweight block ciphers but none of them addressed the specific constraints imposed by the context of the IoT.

The authors of [8] analysed 16 lightweight block ciphers on the MSP430 16-bit microcontroller. The provided C library [9] shows that the project does not use a common interface for evaluating all the

[1] On the other hand, if there is only one single platform to support, as is the case with the "conventional" Internet where the Intel architecture enjoys an almost monopoly, it makes of course sense to use a performance-optimized assembly implementation.

ciphers and it can not easily accommodate new devices. Inspecting the benchmarking code we discovered that the RAM requirement metric is wrongly computed, because the implementers assume that the `unsigned int` data type takes one byte on the target microcontroller instead of two. Although this is the biggest collection of lightweight ciphers implementations available, some of the implemented ciphers do not verify the test vectors provided in the cipher specifications. For the ciphers considered both in our paper and in [8], our results on the same platform are on average two times better.

During the ECRYPT II project, a survey paper [10] concerning the performance evaluation of 12 low-cost block ciphers on AVR ATtiny45 device was published. The set of analysed ciphers includes lightweight ciphers designed until the paper publication and thus it does not contain recent designs. The authors described the methodology used and the requirements formulated to ensure a fair comparison of the lightweight block ciphers. Although the assembly implementations are available [11], there is no framework provided that can help users to asses the performance of new designs in the same conditions. The assembly implementation results of this survey on AVR ATtiny45 are on average three times better than our C implementation results on AVR ATmega128.

The XBX extension [12] to SUPERCOP [4] allowed benchmarking hash functions on embedded devices, adding at the same time two new metrics (RAM and ROM consumption) in the context of the SHA-3 competition [6]. The framework is not maintained any more, but is worth mentioning because of the unitary evaluation across several embedded devices and the results importance in the context of the SHA-3 competition [6].

Our contribution Firstly, we establish two different usage scenarios expected to be good representatives of the actual security-related operations performed by devices communicating in the context of the IoT. Then, we identify flagship microcontrollers with 8-bit, 16-bit and 32-bit microprocessors that have low power consumption and are suitable for use in this context.

Secondly, we designed and implemented a framework evaluating the performance of the studied lightweight block ciphers in the same conditions on the selected devices. This is motivated by the lack of a standard method to evaluate lightweight primitives in the same conditions, on the same devices. The metrics (code size, RAM consumption and execution time) are extracted at a very detailed level and aim to help embedded software developers in choosing the trade-offs that better suit their particular needs.

Thirdly, we release our framework's source code and the lightweight block ciphers implementations. Our aim is to offer a completely free and open environment for fair comparison and evaluation of lightweight block ciphers performances. Thus, we are committed to maintain a web page [13] with the results obtained by different implementations.

Fourthly, we analyse a set of 13 lightweight ciphers using our benchmarking framework and infer interesting relations between the design constructions and the performance figures. The lightweight block ciphers selected cover different design rationals. We also consider recently proposed designs which have not yet been analysed in similar studies.

To the best of our knowledge, this paper is the first to analyse in the same conditions a broad range of lightweight block ciphers on different devices in the context of the Internet of Things. It can be used by embedded software designers to decide which cipher to implement as well as by cryptanalysts selecting their next targets. Our framework allows the user to define a custom "Figure Of Merit" (FOM) according to which the overall ranking will be assembled. The FOM can assign different weights to execution time, RAM, and code size, and may even take into account the security aspects. The *security level* given in Table 1 provides information about the current state of the cryptanalysis of each cipher and should also be considered when choosing a lightweight primitive.

2 Usage Scenarios & Target Devices

We chose to evaluate the studied block ciphers in two usage scenarios that cover the two main security requirements of the IoT embedded devices: communication confidentiality and entity authentication. The target devices are three widely used microcontrollers having low power and energy consumption. We selected these devices because they match the IoT resource constraints and they are representatives of the most used 8, 16 and 32 bits microprocessor.

Scenario 1 – Communication Protocol This scenario covers the need for secure communication in sensor networks and between IoT devices. It assumes that the sensitive data is encrypted and decrypted using a lightweight block cipher in CBC mode of operation. Considering the limitations of communication protocols in sensor networks described in IEEE 802.15.4 [14] and ZigBee [15] standards, the data length exchanged in a single transmission by IoT constrained devices is 128 bytes. Because the message length is fixed to 128 bytes, we do not consider a padding scheme since this introduces unnecessary overhead. The IoT device has the cipher master key stored in RAM and the round keys are computed using the key schedule and then stored in RAM for later use in the encryption process. The data that has to be sent as well as the initialization vector are also stored in the device's RAM. Encryption is performed in place to reduce the RAM consumption. The key schedule does not modify the master key since it may be used later.

Scenario 2 – Challenge-Handshake Authentication Protocol Challenge-handshake authentication covers the need of authentication in the IoT. The scenario assumes an authentication protocol, where the block cipher is used in CTR mode to encrypt 128 bits of data. The device has the cipher round keys stored in Flash memory and there is no master key stored into the device and consequently no key schedule is required. The data that has to be encrypted is stored in RAM, as well as the counter value. To reduce the RAM usage, the encryption process is done in place. This scenario is suitable for very constrained environments where binary code size and RAM usage have to be extremely low, while the execution time should be fast enough to avoid wasting the device battery.

Target Devices The three microcontrollers selected for our evaluation are the 8-bit AVR ATmega128 [16], the 16-bit TI MSP430F1611 [17] and the Arduino Due [18] based on 32-bit ARM Cortex-M3 [19]. They use RISC microprocessors clocked at 16, 8, respectively 84 MHz. For a brief description of each microcontroller see Appendix A.

3 Benchmarking Framework

Most papers introducing a new cipher report performance evaluation on different platforms and usually in different conditions. The results obtained on different devices and in different measurement conditions are then used to compare the new cipher with previous ones. The conclusions are not accurate and do not inspire confidence because it is hard to correctly evaluate different ciphers if comparative implementations are not available. Our benchmarking framework is motivated by the need for a unified evaluation of lightweight block ciphers' performances.

We introduce the tool used to collect performance metrics for lightweight ciphers on three different devices: 8-bit AVR, 16-bit MSP and 32-bit ARM. To increase the level of confidence and transparency in our results, the framework is available for free together with more than 80 implementations of 13 lightweight block ciphers.

We strived to make our framework both easy to use and flexible, hence our choice to benchmark C implementations. Considering that almost all ciphers' reference implementations are written in C, the cipher designer simply has to adapt their reference implementation to the framework requirements to be able to evaluate the new cipher. The C language is widespread and easy to cross compile for the selected architectures. Therefore, a lightweight block cipher's performance can be evaluated on three different IoT platforms with limited efforts.

To ensure a fair evaluation, we formulated a set of constraints that each implementation should follow. The detailed description of the framework requirements is given in Appendix B.

The benchmarking framework is able to extract three primary metrics: code size, RAM consumption and execution time. We consider these metrics because they describe the cipher's characteristics with respect to the IoT device requirements and they can not be inferred from other metrics. We do not consider derived or secondary metrics such as energy consumption, power consumption, etc. Those metrics are closely related to the basic metrics and thus would be redundant. For example, the energy consumption can be computed from the device's energy model and the execution time.

It is difficult to optimize the three metrics simultaneously. Thus, we tried different trade-offs in order to better understand the link between each cipher construction and the performance figures. We introduce the Figure-of-Merit (FOM), which is a weighted sum of each cipher's performance across the three metrics. The results extracted by the framework are very detailed and will help embedded devices programmers to chose between different implementation strategies depending on their particular constraints.

3.1 Code Size

The code size is measured in bytes and corresponds to the program footprint which is stored in the Flash memory of the target device. The code size for each cipher implementation is computed using the `size` tool on object files generated by the compiler. The tool lists the section sizes for each analyzed binary file. To get the code size requirement we add the value of the `text` and `data` sections of the relevant object files. The `text` section of a binary file contains the code, local variables (initialized and uninitialized) and constant variables (global and local), while the `data` section contains global initialized variables. The content of the `data` section is loaded from Flash to RAM at execution time. Since our framework forbids the use of global uninitialized variables in cipher implementation, we do not consider the `bss` section of the binary file, which contains the code size for global uninitialized variables.

The common code parts are considered just once when computing the code size for operations that use the common code several times to encourage code reuse. For example, it can help implementers to decide if they should implement only encryption or encryption and decryption operations. The measurements do not consider the `main` function's code size, where all the cipher operations are put together. This value is the same for all ciphers and is not relevant for the studied scenarios.

3.2 RAM

The RAM consumption is divided into stack consumption and data consumption. The size of the data stored in RAM is computed using the implementation information file and the `size` tool. It includes scenario specific RAM data such as data to encrypt, keys, round keys or initialization vectors. The stack consumption is measured using `gdb`. At the beginning of each of the measured operations, immediately after the function call for that operation the stack is filled with a memory pattern. At the end of the function execution, the values in the memory are compared with the memory pattern and the number of modified bytes gives the stack consumption. There are no arguments saved on the stack that have to be counted, because the measured functions do not use value arguments. The return address is not considered as stack consumption since it is insignificant and the same for all ciphers.

3.3 Execution Time

The execution time is expressed in number of processor cycles spent executing a set of instructions. The metric is extracted for the four basic operations performed by a block cipher. To measure the execution time on AVR we used the cycle accurate simulator `Avrora` [20,21]. For MSP we used the cycle accurate simulator `MSPDebug` [22]. To extract the execution time metric on ARM microprocessor we inserted additional C code for reading the system timer number of ticks at the beginning and at the end of the measured operations. The difference between these values gives the number of cycles required for the measured operation. To extract the values we used the Arduino Due [18] board based on ARM Cortex-M3 [19] microprocessor. The extracted values for ARM may vary depending on how the C instructions are translated into assembly instructions by the compiler in different contexts and how the data types are aligned in memory. This is the reason why we get different cycle count values in different usage scenarios for the same function.

4 Analysed Ciphers

Since our aim is to understand the link between the cipher construction and the performance figures on the selected devices in the IoT context, we selected ciphers representing a large variety of design decisions from the two large families of Substitution-Permutation Networks (SPN) and Feistel Networks (FN).

The AES is the canonical example of an SPN, however other designs for the S-box and the linear layer are of course possible (ex. PRESENT, Robin and Fantomas). The overall structure of the cipher can also vary while still maintaining a round function consisting in an S-box layer and a linear layer: LED adds key material every 4 rounds only while PRINCE implements a unique property called α-reflection.

Feistel Networks can be designed using a small SPN as the Feistel function, as in LBlock or Piccolo, or using simple arithmetic and logical operations as in Simon and in ARX designs like HIGHT, SPECK and RC5. These operation may be data-dependent as is the case in RC5. A variant of the FN is the Generalized FN which uses more than two branches. The way the branches are mixed at the end of each round can consist in a simple rotation (HIGHT) or in a dedicated permutation optimizing diffusion

(TWINE, Piccolo). A high number of branches allows the use of very simple Feistel functions as in TWINE and HIGHT.

Although we included a similar number of hardware and software oriented designs, we notice that the trend is moving from hardware only ciphers (Piccolo, PRINCE) to software friendly designs (Simon, Speck, Fantomas, Robin).

Block sizes of 64-bits are used when available, otherwise 128-bits are used. We use the cipher version with with key length that is greater than or equal to 80 bits, which is considered sufficient in the context of the IoT. We provide a brief description of each cipher and refer the reader to the original papers for more details.

Table 1. Studied ciphers. Block, key and round keys sizes are expressed in bits. Security level is the ratio of the number of rounds broken in a single key setting to the total number of rounds.

Cipher	Year	Block size	Key size	Round keys size	Rounds	Security level	Type	Target
AES	1998	128	128	1408	10	0.70	SPN	SW, HW
Fantomas	2014	128	128	0	12	NA	SPN	SW
HIGHT	2006	64	128	1088	32	0.69	Feistel	HW
LBlock	2011	64	80	1024	32	0.72	Feistel	HW, SW
LED	2011	64	80	0	48	NA	SPN	HW, SW
Piccolo	2011	64	80	864	25	0.56	Feistel	HW
PRESENT	2007	64	80	2048	31	0.84	SPN	HW
PRINCE	2012	64	128	192	12	0.83	SPN	HW
RC5 *	1994	64	128	1344	20	0.90	Feistel	SW
Robin	2014	128	128	0	16	NA	SPN	SW
Simon	2013	64	96	1344	42	0.67	Feistel	HW, SW
Speck	2013	64	96	832	26	0.58	Feistel	SW, HW
TWINE	2011	64	80	1152	36	0.64	Feistel	HW, SW

* We use RC5 with increased number of rounds.

AES has been standardized by the American NIST and is widely used. It has a SPN structure with an internal state of 128-bits represented as 4×4 byte matrix. The `SubBytes`, `ShiftRows`, `MixColumns` and `AddRoundKey` operations are applied to the cipher state [5,23]. The best single-key cryptanalysis of AES-128 is a meet-in-the-middle attack on 7 rounds out of 10 [24].

Fantomas is a 128-bits block cipher similar to Robin. It is a LS-design, meaning that the linear layer consists in the parallel applications of so-called "L-boxes". The S-box structure simplifies the implementation of masking. There is no key-schedule: the master key is added at every round [25]. At the time of writing, there was to the best of our knowledge no attack on this very recently designed block cipher.

HIGHT is a generalized Feistel network with an ARX structure. Indeed, the Feistel functions are built using only XOR and bitwise rotations. The output of the Feistel functions is combined with the other branches using either XOR or addition modulo 2^8 [26]. A saturation attack breaks 22 out of 32 rounds of this cipher [27].

LBlock is a Feistel Network with 32 rounds. The Feistel function consists of a XOR with the round subkey, a substitution layer of 8 different S-boxes and a permutation of 8 nibbles. Furthermore, the content of one of the branches is rotated by 8 bits in each round. The design trade-offs between security and performance led not only to hardware efficiency but also software efficiency [28]. The best cryptanalysis of this primitive is an impossible differential attack on 23 out of 32 rounds [29].

LED is an AES-based cipher aiming at very compact hardware implementation while maintaining reasonable performance in software. The main characteristic of the cipher is the absence of the key schedule, the round keys being replaced with a part of the master key [30]. To the best of our knowledge, there are no attacks on LED-80. However, there is a differential attack covering 16/32 rounds of LED-64 and 24/48 rounds of LED-128 [31]. The structural attack breaking 32/48 rounds of LED-128 presented in [32] is unlikely to be adapted to attack LED-80.

Piccolo is a generalized Feistel structure with four 16-bit branches. To improve diffusion, Piccolo uses a byte permutation between rounds. The Feistel function consists of two S-box layers separated by a diffusion matrix [33]. The best attack on Piccolo-80 is a Meet-in-the-Middle attack presented by its designers in the paper introducing the cipher.

PRESENT is a SPN based block cipher with a bit oriented permutation layer. The non-linear layer is based on a single 4-bit S-box which was designed with hardware optimizations in mind [34]. A truncated differential attack on 26 out 31 of rounds of PRESENT is presented in [35].

PRINCE uses a so-called FX construction, where the first two subkeys are used as whitening keys, while the third subkey is the 64-bit key for the 12 rounds SPN called PRINCE$_{core}$. The cipher introduces the α-reflection property: encryption with one key corresponds to decryption with a related key [36]. The best attack on this cipher is a multiple differential attack on 10 out of 12 rounds [37].

RC5 is a Feistel network which uses data dependent rotations [38]. Though RC5 was designed before lightweight cipher design became popular, it is obviously lightweight, which is confirmed by its wide use in sensor networks. The block and key size as well as the number of rounds can be chosen freely so we study RC5-32/20/16, i.e. a version of RC5 operating on two 32 bit words, using 20 rounds (40 half-rounds) and a 16 byte key. We have chosen the number of rounds so as to have a security level of 0.90. RC5-32/12/16 can be attacked using a differential cryptanalysis [39] which can be extrapolated to 18 rounds but would require almost the full codebook (2^{64} ciphertexts).

Robin is a 128-bits block cipher similar to Fantomas but, for example, its "L-boxes" are involutions. The look-up table-based diffusion layers and the structure of the S-boxes makes the family ciphers good candidates for Boolean masking in bitslice software implementations [25]. There exists a set of weak keys of density 2^{-32} for this cipher which, if used, leads to attack on the full primitive [40].

Simon uses a Feistel structure with a simple round function which uses bitwise XOR, bitwise AND and left circular shifts. It is optimized for performance in hardware implementations, but achieves good results in software also [41]. A differential attack on 28 out of 42 rounds of Simon-64/96 is presented in [42].

Speck is designed to provide excellent results in both hardware and software, but is optimized for software implementation on microcontrollers. It uses a Feistel structure in which both branches are modified at each round using bitwise XOR, modular addition and circular shifts in both directions [41]. The best attack against Speck-64/96 is a differential attack on 15 out of 26 rounds [43].

TWINE is a generalized Feistel Network with 16 branches. The Feistel function consists simply in a key addition and the application of a 4-bit S-box. The linear layer is a nibble permutation with much higher diffusion than a nibble rotation as used e.g. in HIGHT. The cipher design aims at small footprint in hardware implementation and small ROM/RAM consumption in software implementation [44]. The best attack on TWINE-80 is a multi-dimensional zero-correlation linear attack on 23 out of 35 rounds [45].

5 Implementation Aspects

AES Size-optimized implementations of AES put the S-box and the round constants in lookup tables as they occupy slightly more than 256 bytes. The code of the size-optimized implementation mostly follows the cipher pseudocode for all three architectures. The speed-optimized implementation for ARM uses the 32-bit lookup tables that combine the S-boxes with the MixColumns transformation (similarly to well-known x86-optimizations). As these tables are too large (15 KBytes for either encryption or decryption) for AVR and MSP, we use only the Galois multiplication table for these architectures. The C code is based on the CryptoLib implementation [46] and the SUPERCOP implementation by Hongjun Wu [4].

Fantomas is implemented to combine lookup-table based linear diffusion layers (so-called L-boxes) with bit-sliced S-boxes, which are computed using a Feistel structure. Storing the 4×512 KB L-boxes in RAM improves the execution time with one quarter on AVR and ARM. Our implementations are based on non-bitsliced C code provided by the designers.

HIGHT is implemented to follow the specifications from [47], which modifies the design from the original paper [26]. The 128 7-bit δ constants are either computed when the key schedule is called or precomputed and stored in Flash or RAM. The fully unrolled version with inlined auxiliary round functions $\mathtt{F_0}$ and $\mathtt{F_1}$ requires half cycles compared to the reference implementation. The cipher byte level rotations on MSP waste half of the microprocessor registers, while on AVR they can be done without penalty. While AVR has 32 general purpose registers, MSP has only 12. For these reasons, the implementation for MSP requires more than three times more clock cycles than the one for AVR.

LBlock is implemented according to the original specifications [28]. Optimization strategies include performing operations on 8, 16 or 32 bits when possible, storing the S-boxes in Flash or RAM and unrolling the loops. The best execution time on ARM is achieved by the fully unrolled implementation using 32-bit operations, with the S-boxes stored in RAM.

LED is an SPN aimed at very compact hardware implementation. It represents the state by a 4×4 nibble matrix and uses very similar round transformations as the AES, except that it is nibble-oriented. There is no key schedule in LED; the key is simply XORed every 4 rounds. Our implementation of LED combines the SubSell, ShiftRow, and MixColumn operation into a table look-up to reduce execution time.

Piccolo implementation follows closely the cipher description [33]. The arithmetic in GF(2^4) uses only XORs and 2 small look-up tables for multiplications by 2 and 3. The S-box and the key schedule constants are stored in look-up tables. No specific loop unrolling is applied.

PRESENT has a small S-box so its lookup table is used in all implementations. However, its combination with a bit permutation over a 64-bit word is difficult to optimize without using very large (up to 1 MB for decryption) lookup tables. Such tables are affordable only in the speed-optimized implementation for ARM (as in the implementation provided by the BLOC project [9]), whereas for AVR and MSP we had to implement the bit permutation also as a look-up table. The size-optimized implementation follows the cipher's pseudocode and is also taken from [9]. Overall, the bit-oriented structure of PRESENT makes all software implementations very slow unless they can afford very large lookup tables.

PRINCE is implemented after the original paper [36] and [37]. The optimization strategies considered include using 8, 16, 32 and 64 bit operations were possible and different levels of loop unrolling. The best execution times are obtained using fully unrolled implementation with 8-bit operations for AVR and 16-bit operations for MSP. For ARM the best execution times are achieved using a partially unrolled version with 32-bit oriented operations.

RC5 is implemented by adapting the reference implementation provided in [38]. Because of the simple and efficient design, there are not too many optimization directions. To explore different trade-offs, we fully unrolled the cipher operations and we precomputed the encryption key schedule array `S` and stored it in Flash or RAM.

Robin is implemented in different ways that are based on non-bitsliced C code provided by the designers. The two L-boxes are stored in Flash or RAM while the S-box layer is computed at each round using the Feistel structure.

Simon is implemented to optimize for both RAM usage and speed because of Simon's inherent simplicity. It follows the pseudo-code from the specification paper [41]. The rounds are processed by pairs and the rotation functions as well as the Feistel function are inlined. The `Z` constant used in the key schedule is the only lookup table. The C code is written with only 32-bit operations.

Speck is implemented in a straightforward fashion using the pseudo-code from the specifications [41]. It is optimized for both speed and RAM usage. The rounds are processed by pairs and the rotation functions are inlined. The C code uses only 32-bit operations and no look-up table.

TWINE is a very simple cipher so that even the speed-optimized implementation is marginally larger than the size-optimized one. It uses 4-bit branches which, in the authors' implementation [44], reside in separate bytes (so that the entire state is twice as large). We wrote a size-optimized implementation. Both implementations are small enough to run on all platforms. We conclude that TWINE is software-friendly and is one of the easiest ciphers to implement on all platforms.

6 Results

6.1 Methodology

We have gathered and prepared from 2 to 20 implementations for each cipher (more than 80 in total) and benchmarked all of them on each device in each scenario. It is possible to sort all the implementations according to their speed, code, or RAM size in any particular scenario on any device and we maintain a separate interactive web-page [13] where all these orderings can be chosen. Due to space limits for this submission, we have aggregated the data by the following principles, which seem to be the most interesting ones:

– In Scenario 1 we made the full encryption and decryption including the key schedule. Then for each implementation i, and device d we calculate the performance parameter $p_{i,d}$. The value $p_{i,d}$ aggregates three metrics $M = \{$ the code size, the RAM size, the cycle count $\}$ as follows:

$$p_{i,d} = \sum_{m \in M} w_m \frac{v_{i,d,m}}{\min_i(v_{i,d,m})}, \tag{1}$$

where $v_{i,d,m}$ is the value of the metric m for the implementation i on the device d; w_m is the *relative weight* of metric m and $\min_i(v_{i,d,m})$ represents the minimum value of the metric m from all considered implementations on the same device d. For each cipher and each device we set $w_m = 1$ (the framework also allows to choose other weights for the metrics) and select the implementation with smallest $p_{i,d}$. Finally, for each cipher and the selected set of implementations i_1, i_2, i_3 (one for each device) we calculate the Figure-of-Merit (FOM) value as the average performance value over three devices.

$$\text{FOM}(i_1, i_2, i_3) = \frac{p_{i_1,AVR} + p_{i_2,MSP} + p_{i_3,ARM}}{3} \tag{2}$$

Then we sort the ciphers accordingly to FOM (Table 2-I). We also list the encryption and decryption benchmarks alone for the same implementations (Table 2-II,III).

– In Scenario 2, we also select for each cipher and device the best implementation. First, we select the most balanced implementation using Equation (1) and $w_m = 1$ (Table 3). In Table 4-I we calculate $p_{i,d}$ a bit differently:

$$p_{i,d} = \sum_{m \in \{\text{code, RAM}\}} w_m \frac{v_{i,d,m}}{\max_i(v_{i,d,m})}, \tag{3}$$

where $\max_i(v_{i,d,m})$ is the maximum value of Flash (for the code size metric) or RAM (for RAM metric) available on device d (see Section A). Thus we essentially measure the fraction of available memory occupied by the implementation. Finally, in Table 4-II the best implementation for a cipher is the one with the smallest cycle count.

6.2 Comparison with other Benchmarks

Many ciphers in our list have been already benchmarked on AVR, MSP, or ARM architectures separately or within some framework. It is difficult to compare the performance numbers between the frameworks and separate implementations because the methodology is different, the optimization efforts vary, and some assembly implementations can be much faster that the C implementations (which we use). We believe that the unified methodology allows for a good overview and insight into the relative performance of the lightweight ciphers. As our framework is open, we expect to receive other optimized implementations in the future so that eventually we get closer to the absolute performance values for each cipher.

The most notable differences of our benchmarks with existing implementations on AVR/MSP/ARM are the following:

– The BLOC [9] project's MSP implementations of HIGHT, LBlock, Piccolo, and Twine are slightly worse than ours (by the aggregated metric), whereas the implementations of AES and PRESENT are much faster.
– The AVR assembly implementations of PRESENT and AES from ECRYPT project [11] and [48], as well as the implementation of TWINE [44] are much faster than our C implementations up to the factor of 10. Our HIGHT implementation is by factor 5 better than the one in [11] and is on par with [48].
– The designers' assembly AVR implementations of Simon and Speck are about two times as small and five times as fast as ours [49].

6.3 Discussion of Results

In Scenario 1 ("bulk encryption"), the top 7 ciphers based on the FOM score are Speck, Robin, Fantomas, Simon, RC5, LBlock and Hight; all other evaluated algorithms have a FOM score that is more than three times worse than that of Speck. We remind that the FOM score takes into account all three metrics (i.e. execution time, RAM footprint and code size) and does so across three platforms (AVR, MSP, and ARM). Of course, when looking at performance, RAM footprint, or code size individually, or when looking at AVR, MSP, or ARM individually, the specific ranking can differ significantly from the overall ranking based on the FOM score. Furthermore, it has to be taken into account that several (up to 20) different implementations exist for each cipher. Since these implementations are based on different optimization strategies, they can (and usually do) perform differently on the three platforms. Therefore, it happens that one and the same cipher has a worse execution time on 16-bit MSP than on 8-bit AVR (e.g. LBlock, HIGHT), which is not a mistake but simply the result of considering RAM equally important as execution time. On each platform, we collected our benchmarking results using the implementation that achieved the highest FOM score.

When having a closer look at the results on AVR, it turns out that the top-ranked algorithms are very similar in terms of RAM footprint, which means the overall rank is primarily determined by execution time and code size. A somewhat surprising result is that AES is the fastest of all ciphers on AVR, even though it did not make it into the Top 7 because its high performance comes at the expense of very large code size. Robin and Fantomas earned their Top-7 position mainly because of their good execution time, which is only slightly worse than that of AES. The other five ciphers in the Top-7 have the advantage of small code size, but are significantly slower than AES. The situation is somewhat similar on MSP in the sense that the Top-7 ciphers are very close in terms of RAM footprint and AES is again the fastest. Fantomas, Robin, and Speck are the ciphers that come closest to AES in terms of execution time, whereby Robin is not only fast but also features relatively small code size. The execution time of all other ciphers is at least four times worse than that of AES. Finally, on ARM, the winners in the performance competition are Speck, Simon and RC5, which all outperform AES. Interestingly, these three ciphers also have the top positions in terms of code size. This is due to the ARX design strategy with an extremely simple function. All other candidates are significantly slower, significantly larger or both.

The overall ranking in Scenario 2 ("challenge-response authentication") is similar to that of Scenario 1. The top-7 are held by the same ciphers, even though their individual ranking can be different. All algorithms outside the top-7 are at least four times worse with respect to FOM score than the best algorithm, which is again Speck. RC5 climbed from rank 5 to rank 3, mainly because the round keys are pre-computed in Scenario 2, i.e. no key schedule has to be performed. On the other hand, Robin dropped from 2 to 5, mainly because its RAM footprint is the highest on all three platforms, roughly double than that of Speck. LBlock and HIGHT hold again the last two positions among the top-7 (similar to Scenario 1) since they are neither particularly fast nor particularly small. The upper part of Table 4 summarizes the results of the implementations with minimal RAM footprint and code size for each of the 13 ciphers. Speck is the most lightweight candidate and, therefore, the best choice for applications where size is the primary constraint. On all three platforms, Speck has a code size of around 600 Bytes and a RAM footprint of less than 100 Bytes. On the other hand, as shown in the lower part of Table 4, when performance is of primary concern and size does not matter much, then AES is a good choice. The execution time of AES significantly improves when using look-up tables to perform the round transformation, which, of course, comes at the expense of increased code size. Also Speck and Fantomas are performance-wise consistently good on all three platforms.

7 Conclusion

We have established two main usage scenarios that fulfill the needs for secure communication of the constrained devices in the IoT context. Then, we have identified representative devices with 8-, 16- and 32-bit microprocessors that have low power consumption and are suitable for use in this context.

We have designed and implemented a benchmarking framework that ensures a fair and consistent evaluation of lightweight block ciphers' performances using the same conditions on the same devices. The metrics (binary code size, RAM footprint and execution time) are extracted using cycle accurate simulators or development boards. For full transparency, the source code of the framework, together with the implementations of the evaluated ciphers are available for free. We strongly encourage the community to use and contribute to our framework, since it allows easy integration and evaluation of

Table 2. Results for scenario 1. Encrypt 128 bytes of data using CBC mode. For each cipher, an optimal implementation on each architecture is selected.

Cipher	AVR			MSP			ARM			
	Code Size [Bytes]	RAM [Bytes]	Execution Time [cycles]	Code Size [Bytes]	RAM [Bytes]	Execution Time [cycles]	Code size [Bytes]	RAM [Bytes]	Execution Time [cycles]	FOM
I: Encryption + Decryption (including key schedule)										
Speck	**1692**	300	239532	**1342**	300	93239	**792**	332	**19461**	3.8
Robin	4950	266	146173	3170	238	76878	3668	**304**	92150	6.8
Fantomas	5898	262	111701	4164	**234**	57430	4604	308	70042	7.1
Simon	2476	375	390119	8158	392	214745	892	400	25690	7.4
RC5	2616	377	515864	1952	378	482894	1144	408	32865	8.1
LBlock	3086	331	207631	2024	328	313349	2136	406	162576	8.7
HIGHT	2608	342	168569	2368	342	423221	2196	392	173589	9.5
Piccolo	2654	319	407931	1824	318	349423	1604	406	291330	11.4
PRINCE	5650	**241**	280381	4174	240	405552	4660	392	226333	12.4
TWINE	3610	402	384993	3452	352	565495	2464	418	256997	13.2
AES	26800	551	**109446**	20726	574	**54075**	15256	576	40820	20.4
LED	4538	274	2634460	7004	252	2505640	3732	334	692194	40.6
PRESENT	11208	591	3838051	12928	1042	2864032	7372	790	606922	51.4
II: Encryption (without key schedule)										
Speck	**652**	281	114897	**474**	288	47991	**300**	300	**6948**	
Robin	2920	221	69199	1976	204	39350	2236	**288**	45926	
Fantomas	2784	**213**	51471	1954	**202**	29038	2232	**288**	35724	
Simon	832	356	189169	732	376	102775	324	372	12830	
RC5	828	357	182673	492	352	174253	352	376	13108	
LBlock	1336	308	102865	808	310	151463	964	374	78961	
HIGHT	1034	324	85105	804	328	213383	764	368	81660	
Piccolo	1250	300	202033	818	302	171143	728	366	140459	
PRINCE	4520	222	139617	3354	224	202279	3944	352	112772	
TWINE	1530	387	194689	1386	340	277783	936	382	126732	
AES	12422	411	**49127**	8718	392	**22766**	7248	464	18237	
LED	2654	232	1141009	4362	248	1186231	2080	310	327923	
PRESENT	4978	575	1576705	4664	776	922263	3164	614	207040	
III: Decryption (without key schedule)										
Speck	**756**	300	117579	**592**	300	41618	**432**	332	**11796**	
Robin	3054	266	76974	2218	238	37528	2456	**304**	46224	
Fantomas	3626	262	60230	2722	**234**	28392	2884	308	34318	
Simon	960	375	190171	890	392	107074	456	400	12000	
RC5	962	377	184043	646	370	177244	484	408	14180	
LBlock	1424	331	99483	960	328	155426	1080	406	81252	
HIGHT	1130	342	80875	936	342	208114	844	392	90432	
Piccolo	1426	319	204315	1008	318	176946	940	406	149751	
PRINCE	4644	**241**	140587	3496	240	203138	4072	392	113524	
TWINE	1590	402	185419	1516	352	280002	1072	418	125799	
AES	8530	450	**50462**	5106	430	**25096**	3376	504	19039	
LED	2450	274	1493083	3022	252	1318658	2288	334	363807	
PRESENT	5502	591	2221691	7386	1042	1924514	3920	790	396351	

Table 3. Results for scenario 2. Encrypt 128 bits of data using CTR mode. For each cipher, an optimal implementation on each architecture is selected.

Cipher	**AVR**			**MSP**			**ARM**			
	Code Size	RAM	Execution Time	Code Size	RAM	Execution Time	Code Size	RAM	Execution Time	FOM
	[Bytes]	[Bytes]	[cycles]	[Bytes]	[Bytes]	[cycles]	[Bytes]	[Bytes]	[cycles]	
				Balanced (globally efficient)						
Speck	**572**	**49**	14003	**618**	58	6054	**512**	**96**	**904**	3.9
Simon	878	65	24305	940	82	12902	600	104	1376	6.1
RC5	804	59	22395	700	**54**	20543	628	104	1730	6.7
Fantomas	2400	103	**5866**	1920	78	3646	2184	184	4552	8.1
Robin	2434	103	7760	1942	80	4935	2188	184	6187	9.0
LBlock	1320	59	11119	976	58	18988	1192	148	10215	10.0
HIGHT	1084	54	11399	980	62	26728	1008	128	11602	11.0
Piccolo	1178	65	25681	966	70	21448	940	160	18388	14.0
TWINE	1408	59	21637	1570	72	34778	1180	156	15677	14.9
AES	2742	127	22603	8844	92	**2862**	7360	184	2418	15.7
PRINCE	4300	63	17207	3418	70	25340	4076	224	14344	17.9
PRESENT	5172	193	203237	4960	396	115338	3520	260	26279	47.3
LED	2482	86	143253	4422	104	148334	2212	192	41728	48.0

Table 4. Results for scenario 2. Encrypt 128 bits of data using CTR mode. For each cipher, an optimal implementation on each architecture is selected.

Cipher	**AVR**			**MSP**			**ARM**		
	Code Size	RAM	Execution Time	Code Size	RAM	Execution Time	Code Size	RAM	Execution Time
	[Bytes]	[Bytes]	[cycles]	[Bytes]	[Bytes]	[cycles]	[Bytes]	[Bytes]	[cycles]
				I: Small code size & RAM					
AES	2742	127	22603	3124	124	33386	2444	232	19735
Fantomas	2400	103	**5866**	1920	78	**3646**	2184	184	4552
HIGHT	1084	54	11399	980	62	26728	1008	128	11602
LBlock	1268	**46**	16473	976	58	18988	1192	148	10215
LED	2482	86	143253	4042	96	694812	2212	192	41728
PRESENT	1562	83	1937461	3650	352	3497578	1760	280	221471
PRINCE	4300	63	17207	3418	70	25340	4076	224	14344
Piccolo	1178	65	25681	966	70	21448	940	160	18388
RC5	804	59	22395	700	**54**	20543	628	104	1730
Robin	2434	103	7760	1942	80	4935	2188	184	6187
Simon	878	65	24305	940	82	12902	600	104	1376
Speck	**572**	49	14003	**618**	58	6054	**512**	**96**	**904**
TWINE	1408	59	21637	1570	72	34778	1180	140	20505
				II: Best execution time					
AES	12320	359	6651	8844	92	**2862**	7360	184	2418
Fantomas	2400	103	**5866**	1920	78	3646	2088	1176	3524
HIGHT	5718	**47**	6377	13780	64	21882	6920	128	5836
LBlock	8336	50	10263	10556	64	15212	7664	280	7349
LED	2428	262	134997	4422	104	148334	2164	368	35161
PRESENT	4504	2157	160631	4960	396	115338	3520	2308	16761
PRINCE	11262	89	13405	15728	76	21124	13344	328	11775
Piccolo	1178	65	25681	966	70	21448	940	160	18388
RC5	4142	57	22225	700	**54**	20543	1544	100	1396
Robin	2434	103	7760	1942	80	4935	2156	1180	5194
Simon	878	65	24305	940	82	12902	600	104	1376
Speck	**572**	49	14003	**618**	58	6054	**512**	**96**	**904**
TWINE	1408	59	21637	1922	136	23938	1180	156	15677

new C implementations. We are committed to maintaining a web page [13] with results obtained by each submitted implementation.

Using the benchmarking framework, we have evaluated a set of 13 lightweight block ciphers and inferred interesting information regarding the link between the design decisions and performance figures. In particular, we confirm that the NSA designs Simon and Speck are among the smallest and fastest ciphers on all platforms. The LS-designs seem to be a promising research direction, but a closer analysis of the security of these constructions is necessary.

Further research may include the addition of new ciphers, integration of countermeasures against physical attacks, extending the framework capabilities to other lightweight symmetric primitives (stream ciphers, hash functions or authenticated encryption) and the integration of other resource constrained devices.

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A Target Devices

8-bit AVR ATmega128 Microcontroller

The ATmega128 [16] microcontroller manufactured by Atmel uses an 8-bit RISC microprocessor which supports 133 instructions. Most of the instructions are encoded into 16-bit and require a single clock cycle to execute. The two stages, single level pipeline allows the execution of instructions in each clock cycle because while one instruction is executed the next one is fetched from the program memory.

The 32 8-bit general purpose registers (`R0` – `R31`) are directly connected to the Arithmetic Logic Unit (ALU), allowing two independent registers to be accessed in one single instruction executed in one clock cycle. The ALU operations are divided into three main categories: arithmetic, logic and bit-functions. Six of the 32 registers can be used as three 16-bit indirect address register pointers (`X`, `Y` and `Z`) for addressing the data space.

The Harvard memory architecture maximizes performance and parallelism. Memory includes 128 KBytes of Flash, 4 KBytes of SRAM and 4 KBytes of EEPROM for data storage. Each program memory address contains a 16-bit or 32-bit instruction. The data memory supports five different addressing modes: direct, indirect, indirect with displacement, indirect with pre-decrement and indirect with post-increment.

The Atmel ATmega128 is a powerful microcontroller that provides a highly flexible and cost effective solution to many embedded control applications from building and home automation to medical and healthcare systems. Among the best microcontrollers when it comes to power consumption, ATmega128 is working at supply voltages between 4.5 and 5.5 volts and has six different software selectable power modes of operation.

16-bit MSP430F1611 Microcontroller

The MSP430F1611 [17] microcontroller produced by Texas Instruments uses a 16-bit RISC architecture with an instruction set consisting of 27 core instructions and 24 emulated instructions. Each instruction uses an even number of bytes (two, four or six). There are three core instructions formats: dual-operand, single operand and jump. The number of clock cycles required by an instruction depends on the instruction format and addressing mode used.

The microprocessor supports seven addressing modes: register, indexed, symbolic (PC relative), absolute, indirect register mode, indirect autoincrement, immediate. It has 16 16-bit registers (`R0 - R15`) from which 12 are general purpose registers (`R4 - R15`). The register operations take one cycle.

The Von Neumann memory consists in 48 KBytes of Flash and 10 KBytes of SRAM. The Flash memory is bit, byte and word addressable and programmable.

This microcontroller's typical applications are sensor systems, industrial control and hand-held meters. It supports five power saving operating modes which can be configured by software.

32-bit ARM Cortex-M3 Microcontroller

The Arduino Due [18] microcontroller is based on the Atmel SAM3X8 32-bit ARM Cortex-M3 [19] processor. The Thumb-2 instruction set used by the 32-bit RISC processor ensures high code density and reduced program memory requirements. The high performance processor core uses a three stage pipeline Harvard architecture. It has 13 32-bit general purpose registers (`R0 - R12`), which can be used for data operations.

The microcontroller provides 512 KBytes of Flash organized in two banks of 256 bytes with 1024 pages each and 96 KBytes of SRAM split in two banks of 64 KBytes and 32 KBytes.

ARM Cortex-M3 is the industry-leading 32-bit processor for highly deterministic real time applications. Characterized by ultra-low power consumption, it is suitable for a wide range of low cost platforms: microcontrollers, automotive systems, industrial control systems, wireless networking and sensor nodes.

B Requirements

To unify evaluation conditions, our framework imposes some requirements on each block ciphers' implementations. Firstly, basic operations must be performed by functions having the following signatures.

```
void RunEncryptionKeySchedule(uint8_t *key, uint8_t *roundKeys);
void Encrypt(uint8_t *block, uint8_t *roundKeys);
void RunDecryptionKeySchedule(uint8_t *key, uint8_t *roundKeys);
void Decrypt(uint8_t *block, uint8_t *roundKeys);
```

Each of the above functions should be implemented in its own C file. If the cipher key schedule is the same for encryption and decryption then only the encryption key schedule function should be implemented. The framework will take the use of a common key schedule into account when computing the different metrics.

Secondly, all common code sections should be implemented as distinct functions to reduce the code size. In this case, the implementer has to add the common code files names to the implementation info file, which is parsed by the framework when extracting the metrics for the implementation.

Thirdly, we give the implementer the possibility to chose where to store the constants used by the cipher: in Flash/ROM or in RAM. This flexibility has a price: the implementer has to define and use a dedicated macro to read the respective constant value. Fourthly, the implemented lightweight cipher's block size in bits has to be equal to or divide 128.

While these requirements are formulated to guarantee the same evaluation conditions for an accurate assessment of block ciphers' performances, they limit the possibility to benchmark highly optimised implementations such as bit sliced versions. Yet our aim is not to assess extreme optimizations, which are likely to never be used in practice because of the unreasonable trade-off (i.e. a very fast cipher implementation that uses all available memory has no real world application since there is no space left for other features).

The framework is able to automatically verify the implementation compliance with the formulated requirements and check the implementation's correctness using the provided test vectors. The metrics extraction process is completely automated and remains easy even for users with little experience. We are committed to maintaining a web page [13] with results obtained for each submitted implementation and strongly encourage the community to contribute with implementations to our framework. We think that a common, open and free environment can create a culture of fair comparison of lightweight block ciphers.