Design Space Exploration for Ultra-Low Energy and Secure IoT MCUs

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This paper explores the design space of secure communication in ultra-low-energy IoT devices based on Micro-Controller Units (MCUs). It tries to identify, evaluate and compare security-related design choices in a Commercial-Off-The-Shelf (COTS) embedded IoT system which contribute in the energy consumption. We conduct a study over a large group of software-implemented crypto algorithms: symmetric, stream, hash, AEAD, MAC, digital signature and key exchange. A comprehensive report of the targeted optimization attributes (memory, performance and specifically energy) will be presented from over 450 experiments and 170 different crypto source codes. The paper also briefly explores a few system-related choices which can affect the energy consumption of secure communication, namely: architecture choice, communication bandwidth, signal strength and processor frequency. In the end, the paper gives an overview on the obtained results and the contribution of all. Finally it shows, in a case study, how the results could be utilized to have a secure communication in an exemplary IoT device. This paper gives IoT designers an insight on the ultra-low-energy security, helps them to choose appropriate cryptographic algorithms, reduce trial-and-error of alternatives, save effort and hence cut the design costs.

CCS Concepts: • **Security and privacy → Cryptography**; • **Hardware → Power and energy**.

Additional Key Words and Phrases: Ciphers, Cyber-physical systems, Cryptography, Embedded software, Energy consumption

ACM Reference Format:
Ehsan Aerabi, Milad Bohlouli, MohammadHasan Ahmadi Livany, Mahdi Fazeli, Athanasios Papadimitriou, and David Hely. 2020. Design Space Exploration for Ultra-Low Energy and Secure IoT MCUs. 1, 1 (February 2020), 26 pages. https://doi.org/0000001.0000001

1 INTRODUCTION

Global trends for ubiquitous computing and new advances in computer networks and cyber-physical systems (CPS) have served to foster the emerging era of the *Internet of Things (IoT)* with countless smart objects being connected to the Internet. Smart buildings, factories, farms, cities, wearable and implantable medical devices are being materialized. It is expected that the IoT is consisted of 30 billion smart *things* by 2020[1]. Many of these IoT devices are mobile embedded systems with limited resources, because they should be price-competitive and (ultra) low-energy. They generally come with low power Micro-Controller Units (MCUs) and limited memory. In some cases, like battery-less RFIDs and implantable medical devices, critical energy provision should be taken into account.

Emerging energy harvesting technologies [2, 3] necessitate even more precise energy provisioning for battery-less devices. For these devices, an energy harvester converts an environmental energy resource into the electrical current. Some examples are solar cells and piezoelectric generators in wearable devices[4] and fuel cells in medical implants[5]. Obviously, the amount of the harvested energy is variable and the device

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XXXX-XXXX/2020/2-ART $15.00
https://doi.org/0000001.0000001

should comply with the existing energy to complete its tasks. Therefore, IoT designers are usually challenged to identify the available *choices* or *parameters* that they can modify in order to optimize the design *attributes* like the energy consumption, performance and memory.

Recent reported attacks and privacy concerns oblige IoT devices to apply modern cryptography as the solution for a majority of the security threats [6]. Unlike personal computers with bountiful computation and memory resources, embedded system designers are challenged to utilize lightweight cryptographic primitives in order to minimize the memory size and energy consumption and maximize the performance[7].

Cryptography is one of the most frequent and complex tasks in an IoT device which is executed for each data transmission (and for storage in several cases). Therefore, appropriate algorithms and mechanisms are needed to cope with the limited energy profile. During the last decade, several cryptographic primitives have been introduced including stream ciphers, asymmetric and symmetric block ciphers and hash functions. Each primitive may target either software or hardware implementations or both. From a designer's point of view, there are plenty of cryptographic algorithms available to be integrated into an IoT solution, each of which destined different criteria whether it is code size, performance, chip area , memory or energy consumption. Therefore, a designer may choose a subset which is well suited with the targeted platform, whether it is a Field-Programmable Gate Array (FPGA), Application Specific Integrated Circuits (ASIC) or COTS CPUs with the aim to maximize security and performance at the minimum costs (*e.g* energy, code size, etc). In order to choose one appropriate cipher (among many options), it is necessary to have an insight on the energy costs of each one and how cryptography choices (like key size) affect them. The importance of this insight will intensify with the perspective of the IoT trend, because devices tend to have more communication and hence need executive processing for cryptography which makes them even more dependent on the limited battery-based energy reserves. Therefore, any decision on cryptography can negatively affect the battery life. Especially in the case of dependable applications, such as medical implants, battery life becomes a crucial factor, which must be taken into account from the beginning of the design phase [2, 8].

We target security of ultra-low-energy commercial-of-the-shelf (COTS) CPUs in this paper. Using off-the-shelf CPUs, has several advantages for manufacturers of embedded devices. It considerably reduces the hardware design costs and time-to-market gap. Moreover, such CPUs are robust and mature. Designers also can take advantage of the previously developed tool-chains like compilers and debuggers for the targeted CPU. The overall design cost for low- to mid-scale production justifies using COTS-based CPUs.

Using COTS-based CPU usually imposes software-implemented cryptography (except for high-end CPUs with crypto-processors). There exists a significant number of software-oriented cryptographic algorithms which have been designed with the insight to compile and run optimally using common CPUs instructions. Therefore, the scope of this paper entails software cryptography.

This paper gives IoT designers an insight on the ultra-low-power security, helps them to choose appropriate cryptographic algorithms, reduce trial-and-error of alternatives, save effort and hence cut the design costs.

The contribution of the paper is to identify, explore and analyse the design choices and their impacts on the attributes and costs of a secure IoT system with the focus on the energy consumption. We only focus on the software realm and what a software designer can control on a COTS-based system design. Briefly, the contributions of this paper are five-fold:

- This paper attempts to identify design choices associated with secure communication and quantify their contributions on the system costs. In order to explore the influential design parameters in a secure IoT device, we identified and categorized a comprehensive set of design parameters from two aspects: *Cryptography* and *System*.
- In order to explore security-related design choices, this work identifies over 80 different software cryptographic functions, ciphers and mechanisms. This also includes a list of the previous benchmarking reports on these ciphers. We will explain why the previous benchmarking and comparison works are not enough and a new study is needed by the designers of IoT devices.
- In order to present consistent and comparable results on each domain and its corresponding subdomains, the paper provides a comprehensive benchmarking reports on over 170 cipher source codes using over 450 separate experiments which we have carried out in our laboratory. The source codes have been clustered and shared in a public repository for further researches.

- The paper draws a comparative overview upon all the experiments that have conducted and the information that have been gathered which helps the readers to conclude about the contribution of each parameter on the system energy consumption as well as other costs. As the experiments have been performed on the same test-bed, the results can be consistently compared against each other.
- Through a case study, the paper gives an example of how the obtained results could be used in designing a low energy embedded system. The case study encompasses a medical implant which harvests solar energy for its operation.

For further investigations by future works, we gathered all the source codes used in this report in a repository which is available online[9].

This paper continues on Section 2 with the required backgrounds and an explanation on the methodology. Then Section 3 covers the related work. Section 4 and 5 provide the design space exploration results for "system" and "Cryptography" domains respectively. Section 6 presents a big picture of the obtained results explain how they can be used in a case study. Section 7 follows some discussion on the obtained results and finally, this paper ends with a conclusion in Section 8.

2 BACKGROUND & METHODOLOGY

In this section we briefly introduce the background of the cryptography space and the assumptions and methodology used to explore it.

2.1 IoT Security Requirements

2.2 Identifying Design Choices, Parameters and Techniques

Our assumptions for security services for embedded IoT communication is as follows: The IoT device needs to establish a secure connection session and exchange information with a remote server or cloud system. In ultra-low-power cases, the IoT device may connect to a close proxy device (*e.g.* a cell phone) using an ultra-low power wireless communication technology (*e.g.* Bluetooth Low Energy - BLE[10]) which relays information back and forth between the IoT device and the remote server or cloud system[8].

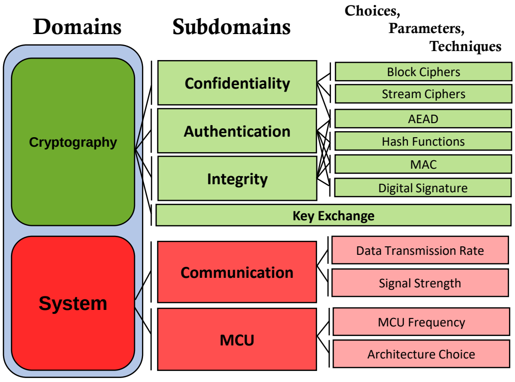

Fig. 1. Abstraction Levels of Cryptography Implementation on MCUs

First of all, each side of communication should authenticate itself to the other side and establish or exchange a session key. The session key is either a random number generated by one side or a combination of two random numbers from both sides of the communication. Afterwards, they can start a secure communication using the session key. They can exchange messages only with authentication or both encryption and authentication (authenticated encryption). Data integrity is commonly associated with that. Therefore the required services could be 1) Secure key establishment 2) Confidentiality 3) Authenticity and 4) Integrity.

In this section, we identify and categorize the design space into domains and sub-domains in order to explore the design space of the secure and embedded IoT design. The aim of this perspective is to identify, benchmark, study and compare major implementation parameters from an IoT designer's point of view. Figure 1 presents this categorization. The domains of *system* and *cryptography* are comprised of different sub-domains:

2.2.1 System Domain. At the system domain, we consider the *MCU* and the *communication* sub-domains. For the MCU domain, we try to find the energy reduction benefits that can be obtained by alternating among different CPU architectures. Also, the effect of MCU operating frequency on the power consumption will be studied.

At the communication sub-domain, we study the effect of the *data transmission rate* and the *signal strength* on the energy consumption.

Table 1. A list of lightweight block ciphers

Cipher	Reference	Key Size	Block Size	Year	Attacks
AES	[11]	128/192/256	128	2000	[12–14]
Camellia	[15]	128/192/256	128	2000	[16, 17]
Clefia	[18]	128/192/256	128	2007	[19, 20]
DESLX	[21]	184	64	2007	-
GOST	[22]	256	64	1970	[23]
Hight	[24]	128	64	2006	[25–28]
Iceberg	[29]	128	64	2004	[30, 31]
Idea	[32]	128	64	1991	[33, 34]
ITUbee	[35]	80	80	2013	[36]
Katan	[37]	80	32/48/64	2009	[38, 39]
Ktantan	[37]	80	32/48/64	2009	[40]
Khudra	[41]	80	64	2014	[42, 43]
Klein	[44]	64/80/96	64	2012	[45, 46]
Lblock	[47]	80	64	2011	[48–52]
LEA	[53]	128,192,256	128	2014	[54, 55]
Led	[56]	64/128	64	2011	[57, 58]
LS-Design	[59]	128	128	2015	[60]
mCrypton	[61]	64/96/128	64	2006	[62]
Mibs	[63]	64/80	64	2009	[64, 65]
Midori	[66]	128	64/128	2015	[67–69]
Misty1	[70]	128	64	1997	[71, 72]
Mysterion	[73]	128/256	128/256	2015	-
Noekeon	[74]	128	128	2000	[75]
Picaro	[76]	128	128	2012	[77]
Piccolo	[78]	80/128	64	2011	[79, 80]
Present	[81]	80/128	64	2007	[82–84]
Prince	[85]	128	64	2012	[77, 86, 87]
PRINTcipher	[88]	48/96	48/96	2010	[89, 90]
Puffin-2	[91]	80	64	2009	[92]
RC2	[93]	8-1024	64	1998	[94]
RC5	[95]	0-2040	32/64/128	1995	[96, 97]
RC6	[98]	128/192/256	128	1998	[96]
Rectangle	[99]	80/128	64	2015	[100]
RoadRunneR	[101]	80/128	64	2015	[102]
Sea	[103]	48,96,...	48,96...	2006	-
Seed	[104]	128	128	2005	[105]
Serpent	[106]	128/192/256	128	1998	[107]
Simeck	[108]	64/96/128	32/48/64	2015	[109]
Simon	[110]	64...256	32...128	2015	[111–114]
SKINNY	[115]	arbitrary	64/128	2016	[116]
Skipjack	[117]	80	64	1999	[118]
SPARX	[119]	128/256	64/128	2016	[120]
Speck	[110]	64...256	32.128	2015	[121, 122]
Tea	[123]	128	64	1995	[124]
Twofish	[125]	128/192/256	128	1994	[126]
Twine	[127]	80/128	64	2011	[128]
Xtea	[129]	128	64	1997	[124]
Zorro	[130]	128	128	2013	[131]

Table 2. Lightweight stream ciphers

Cipher	Ref.	Key Size	Year	Attacks
ChaCha	[132]	256	2008	[133, 134]
F-FCSR-H V3	[135]	128	2009	[136, 137]
F-FCSR-16	[135]	128	2009	[136, 137]
Grain	[138, 139]	80/128	2006	[140]
Rabbit	[141]	128	2004	[142]
Trivium	[143]	80	2006	[144]
Mickey v2	[145]	80/128	2008	[146]
HC-128	[147]	128	2008	[148]
HC-256	[149]	256	2004	[148]
Snow3G	[149]	128	2006	-
Sosemanuk	[150]	128	2008	[151]
Salsa20	[152]	256	2008	[134]

Table 3. Lightweight hash functions

Algorithm	Ref.	Digest(bits)	Year	Attacks
BLAKE2	[153]	224/256/384/512	2013	[154]
Grøstl	[155]	8 to 512	2009	[156, 157]
JH	[158]	224/256/384/512	2008-2012	[159]
Keccak	[160]	224/256/384/512	2013	[161–163]
PHOTON	[164]	80/128/160/224/256	2011	[165]
QUARK	[166]	136/176/265	2013	-
SipHash-2-4	[167]	64/128	2012	[168]
Skein	[169]	256/512/1024	2010	[170, 171]
SPONGENT	[172]	80/128/160/224/265	2013	-

Table 4. A list of message authentication codes (MAC)

Name	Ref.	Application/Standard
CBC-MAC	[173]	ZigBee, IEEE802.11i(WPA2), IPSec, TLS1.2, Bluetooth4.x
OMAC-CMAC	[174]	
PMAC	[175]	ANSI C12.22
XCBC-MAC	[176]	
HMAC	[177]	IPSec, TLS

Table 5. Digital signature mechanisms

Mechanism	Description	Ref.
DSA	Digital Singnature Algorithm	[178]
EC-DSA	Elliptic-Curve DSA	[179]
Ed25519	Edwards-curve DSA	[180]
NTRU-PASS	Polynomial Authentication and Signature	[181]
RSA-PSS	RSA Probabilistic Signature Scheme	[182]

2.2.2 Cryptography Domain. The cryptography domain encompasses the services that previously assumed for an IoT device. As there are plenty of primitives available on the literature, we will examine and compare a comprehensive set of them in our measurement setup. This will form a significant part of the contribution of this paper. At the end, we can compare the cost of each algorithm in each cipher category. The categories include: symmetric block ciphers, stream ciphers, Authenticated Encryption with Associated Data (AEAD) and hash functions, Message Authentication Code (MAC) structures, digital signature and key exchange. Here is a short explanation for each category including a list of their algorithms and primitives.

Block (symmetric) ciphers are a group of deterministic functions which are used to encrypt bulk data in form of blocks. Table 1 presents the list of the block ciphers. We have evaluated a large group of them, namely those which we had access to their source codes. Table 1 (as well as the other primitives in this section) presents also the reported attacks for each primitive in the last column. We should note that the attack list is not exhaustive. Moreover, reported attacks have different severity. Studying the severity of each attack is beyond the scope of this paper. Finally, newer and less-known primitives may have less or no reported attacks. In conclusion, a cipher which has more reported attack is not necessarily less secure.

Stream ciphers are symmetric functions and like block ciphers, provide data encryption. The difference is that they are mainly bit-oriented. Table 2 provides a list of stream ciphers.

Cryptographic hash functions are a group of one-way deterministic functions which have several applications in cryptography. A hash function projects an unlimited or a very big-size message into a relatively small and fixed size *digest*. This digest then is used in cryptographic mechanisms like in message authentication codes or digital signatures. Table 3 presents a list of hash functions measured in this work. The list includes NIST[1] SHA3 competition[2] finalists as well as some famous hash functions which have been invented after the SHA3 competition. namely, `PHOTON`, `QUARK`, `Sip-Hash`and `SPONGENT`[183].

Message Authentication & Digital Signature is accomplished by attaching a short tag to the data being transmitted in order to provide sender authentication on the receiver side. The tag is a small piece of information derived from the plain-text (usually by means of hash functions), encrypted and then sent along with the message which proves the sender's identity and the integrity of the message. Message authentication can utilize symmetric or asymmetric encryption. The symmetric model is called message authentication code (MAC) and the asymmetric one is called digital signature. Table 4 and Table 5 contain a list of well-known MAC and digital signature mechanisms, respectively. For digital signature, we will cover a list from Table-5.

Authenticated Encryption with Associated Data (AEAD) is a group of cryptographic structures which are designed to provide both secrecy (confidentiality) and authenticity (and hence integrity) in network communications. Previous authenticated encryption structures were normally a combination of encryption algorithms to provide confidentiality along with Message Authentication Codes (MAC) for authentication purposes. Table 6 presents a list of the old AE structures which we will not examine in this study. AES-GCM[184] is one of the most frequent authenticated encryption structures which is used in IEEE 802.1AE (MACsec[185]), TLSv1.2[186], IEEE 802.11ad (WiGig)[187], IPSec[188], SSH[189], OpenVPN[190], etc.

In 2012, the international cryptologic research community initiated CAESAR competition[203], which is an abbreviation for "Competition for Authenticated Encryption: Security, Applicability, and Robustness". The goal was to improve some features over AES-GCM. A large number of volunteers participated in their performance analysis and after six years and three rounds of competition, eventually in March 2018, seven AEAD finalists have been announced. namely: ACORN, AEGIS, Ascon, COLM, Deoxys-II, MORUS and OCB(Table-7). We only examined the finalists, as they are expected to replace the old AE mechanisms.

Table 6. A list of conventional authenticated encryption mechanisms

Protocol	**Ref.**	**Year**	**Application/Standard**
CCM	[191]	2007	ZigBee, IEEE 802.11i(WPA2), IPSec, TLS 1.2, Bluetooth 4.0
CWC	[192]	2004	
EAX	[193]	2003	ANSI C12.22
GCM	[194]	2005	IEEE802.1AE(MACsec), IEEE802.11ad(WiGig), Fibre Channel Security Protocols, IEEE P1619.1 tape storage, IETF IPsec standards, SSH and TLS 1.2.
IAPM	[195]	2000	
OCB	[196]	2003	IEEE 802.11 IEEE 802.11(Optional), ISO/IEC 19772:2009, RFC 7253

Table 7. CAESAR competition finalists

Mechanism	Ref.	Key(bit)	MAC(bit)	Year
ACRON v3	[197]	128	128	2016
AEGIS v1.1	[198]	128	128/256	2016
ASCON v1.2	[199]	128	128	2016
Deoxys-II v1.41	[200]	141	128/256	2016
Morus v2	[201]	64/128	128/256	2016
OCB v1.1	[202]	64/96/128	128/192/256	2016

For *key exchange protocols*, we examined the classic Diffie-Hellman and Elliptic-Curve Diffie-Hellman(ECDH) scheme based on curve25519[204] which has been widely adopted in recent libraries and applications (*e.g.* OpenSSH).

2.3 Source Codes

We gathered all the source codes and published them in a repository[9] and made it available for other researchers to participate and upload optimized versions in the future and compare them with the previous ones.

In order to collect the source codes, we utilized several libraries and online repositories; namely, Wolfcryp library[205] LibTomCrypt[206], Supercop [207] and several other pages. Due to the lack of space, we provides the links[3] of the original repositories along with the ciphers names in our Github database[9].

It is worth to mention that the set of cryptographic services and mechanisms mentioned here is not exhaustive. There are other services which are not normally considered as an embedded device security requirement, like blind authentication, secret sharing or secure multi-party computation. Hence we exclude them in this study.

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[1] National Institute of Standards and Technology

[2] https://csrc.nist.gov/projects/hash-functions/sha-3-project

[3] https://github.com/ehsanaerabi/BlockCiphers/blob/master/README.md

2.4 Targeted Optimization Attributes and Costs

We chose a set of attributes to report in our experiments which is normally assumed the optimization target for an ultra-low-power IoT designer. Here is a list of these attributes associated with the "cryptography" domain described in the previous section:

- *Per-bit Energy Consumption*: The main attribute of a crypto task with regards to the aim of this paper is the energy consumption. As it was previously mentioned, it can determine the battery life or in case of an energy-harvested IoT device, it can determine how many crypto tasks the IoT device can fulfill before its harvested energy is exhausted. We report this attribute in form of nano Joule per bit (*nJ/bit*) in order to make it independent from the MCU frequency and the crypto input block size. Therefore, it reports how much energy is required to encrypt a bit of information.
- *Per-bit Performance*: In real-time or interactive IoT devices, the performance can determine the device's responsiveness. We show this attribute in form of *cycle/bit*. It shows how many cycles are needed in order to process a bit of information.
- *Memory*: in form of bytes determines how much memory is required for the crypto binary and its constants (to be stored in ROM) and also for its data during the computation (to be stored in RAM).
- *FOM*: Some previous work(*e.g.* [208]) used Figure-of-Merit (FOM) as a combined metric to compare ciphers in terms of memory, energy or performance. We also use a similar formula which combines memory usage and energy consumption for encryption and decryption to calculate FOM:

$$FOM = w_{mem}.(ROM + RAM) \times w_{eng}.(E_{Enc.} + E_{Dec.})/2 \tag{1}$$

  In which, w_{mem} and w_{eng} are importance weights and were assumed '1' for simplicity. A designer can balance them based on the design cost criterion.

For the "system" domain we have used these attributes specifically when we wanted to compare different architecture choices:

- *Unit price:* which affects the price of the final product and is important in mass production and competitive markets.
- *Memory:* on-chip RAM and ROM.
- *Maximum frequency:* which is directly associated with the system performance.
- *Minimum active current consumption*: normalized in the form of uA/MHz, which affects the energy consumption.

2.5 The Dedicated Platform

The main part of this paper is crypto benchmarking on an emmbedded IoT platform. As the test-bed, we chose Nordic-Semiconductor nRF51822[209], an ultra low power 32-bit System on Chip (SoC) equipped with Bluetooth 4.0 LE, as our targeted device. It is built around a Cortex M0 which have 256KB flash and 32KB RAM memories and is able to operate on 16 and 32MHz oscillator frequencies and a wide supply voltage of 1.8 V to 3.6 V. It comes with flexible power management schemes. Therefore, this device is an appropriate choice for low power wireless applications. All the source codes were compiled using GCC with optimization level 3[210]. In order to calculate the energy consumption, we inserted a shunt resistor at the positive supply voltage (V_{dd}) path and connected probes of a digital oscilloscope to both ends of the resistor. All the power traces are read from the oscilloscope operating at 1GHz sampling rate and processed by a post-processing tool developed in MATLAB in our laboratory. A trigger signal determined the start and end of the crypto algorithm. The post-processing tool uses the captured data to calculate the energy consumption by means of discrete integration and also to determine the execution time using the trigger signal. Therefore, the results are based on the data from real executions and not based on a debugger emulation.

Beside the nRF51822 board, we required an 8-bit MCU for a case study comparison later in Section 4. We chose an Arduino Uno board which is built around an Atmega328 AVR MCU[211]. Atmega328 is an 8-bit microcontroller 32KB flash and 2KB SRAM memories. It can operate with the frequency up to 20MHz.

3 RELATED WORK

Eisenbarth *et.al* published one of the first lightweight block ciphers comparison reports in 2007. Since then, several reports have been published by researcher in an effort to characterize lightweight block ciphers.

Table 8. Previous work on block cipher benchmarking

	Reference	Year	#Ciphers	Platform	Perform.	Area	Memory	Energy
Block Ciphers								
1	Eisenbarth *et al.*[212]	2007	8	8-bit AVR	*		*	
2	Rolfes *et al.*[213]	2008	1	ASIC 180-250-350nm	*	*		*
3	Yalla *et al.*[214]	2009	2	FPGA	*	*	*	*
6	Eisenbarth *et al.*[215]	2012	12	8-bit AVR	*		*	*
7	Kerckhof *et al.*[216]	2012	6	ASIC 65nm	*	*		*
8	Hanley *et al.*[217]	2012	2	FPGA	*	*		*
9	Batina *et al.*[218]	2013	7	ASIC 130nm	*	*		*
10	Manifavas *et al.*[219]	2013	16	8-bit AVR/FPGA	*	*	*	
11	Cazorla *et al.*[220]	2013	18	16-bit MSP430	*		*	
12	Beaulieu *et al.*[221]	2014	10	8-bit AVR	*		*	
13	Malina *et al.*[222]	2014	20	Java	*			
14	Dinu *et al.*[208]	2015	13	AVR-MSP-ARM	*		*	
15	Yang *et al.*[223]	2015	2	ASIC 65nm	*	*		*
16	Banik *et al.*[224]	2015	9	ASIC 90nm	*	*		*
17	Bogdanov *et al.*[225]	2015	2	ASIC 130nm	*	*		*
18	Diehl *et al.*[226]	2017	6	FPGA- 16-bit MSP430	*	*		*
19	Hatzivasilis *et .al*[227]	2014	6	ARM Cortex-A8	*		*	
Hash functions								
1	Balasch *et al.*[228]	2012	18	8-bit AVR	*		*	
2	Homsirikamol *et al.*[229]	2015	5(SHA3)	FPGA	*	*		
MAC								
3	Hatzivasilis *et .al*[227]	2014	8	ARM Cortex-A8	*		*	
Stream Ciphers								
1	Fournel *et al.*[230]	2007	13(eSTREAM)	32-bit ARM	*		*	*
2	Good *et al.*[231]	2007	9(eSTREAM)	ASIC	*	*		*
3	Manifavas *et al.*[232]	2016	6	ARM(A9)-FPGA-ASIC	*	*	*	*
4	Hatzivasilis *et .al*[227]	2014	9	ARM Cortex-A8	*		*	
Authen. Enc.								
1	Simplicio *et al.*[233, 234]	2011	6	16-bit MSP430	*		*	*
2	Krovetz *et al.*[235]	2011	6	Intel/ARM/PowerPC/SPARC	*			
3	Ankele *et al.*[236]	2016	21(CAESAR)	Intel Core.i5	*			
4	Diehl *et al.*[226]	2017	29(CAESAR)	FPGA	*	*		

Table 8 presents previous block cipher benchmarking works including their references, year of publication, number of ciphers tested, platform and also the type of information that they provide on their results like: energy, performance, code size (for microprocessors) and area (for FPGA and ASICs). Six reports exist on microprocessors and one of them([208]) has used a 32-bit architecture (ARM) which itself lacks reporting on energy consumption.

Table 8 presents related benchmarking reports on hash functions. The number of reports is limited in comparison to the block ciphers and the first work has been published in 2012[228].

Concerning stream cipher benchmarking (Table 8), the first benchmarking paper was published in 2007[231]. The evaluation in this paper is on the eSTREAM[237] project's stream ciphers and results include energy consumption along with other parameters on 32-bit ARM-9. But the MCU and the ciphers they used are now outdated after a decade. The work of [232] Manifavas *et al.* includes comprehensive results on different platforms, but they have used ARM Cortex-A9 which targets high-end computers, tablets and cell phones.

MAC structures mainly use block ciphers as their building blocks in their construction and hence their cost normally are associated with the cost of the block cipher they employ. The only related work we found on this part is [238] which uses high-end CPUs from Intel and AMD in their evaluation.

There are few benchmarking reports on the previous rounds of the CAESAR competition which concern high-end Intel Core.i5 processors and FPGAs[239, 240]. Their goal was to compare the performance of the competitors. Therefore, still comprehensive benchmarking reports on embedded processor are needed on finalists.

4 SYSTEM DOMAIN EXPLORATION

In this part, we explore the system domain of the design space described in Figure 1. We separate the design parameters into two categories: "MCU" and "communication".

4.1 MCU Subdomain

Here we investigate the effect of two options at the MCU level on the targeted parameters: 1) MCU data-path choices 2) MCU operating frequency.

4.1.1 MCU data-path choices. To see the effect of MCU data-path choices on the targeted parameters, we performed two studies. Firstly, we gathered a list MCUs available "off-the-shelf" to an IoT designer and compared them. Secondly, we conducted a case study experiment on an 8-bit and a 32-bit MCUs to see their differences. Here is an overview of them:

Off-the-Shelf MCUs study: We chose and studied a set of 8-bit, 16-bit and 32-bit MCUs from different manufacturers [4] . In order to align similar MCUs, first we considered a specific price window (around 1.5 Euros per unit) and gathered a list of MCUs in the price range from online distributors. Figure 9 presents the information extracted from their data-sheets. The MCUs are classified based on their data-widths. For comparison purposes, some parameters in the Table 9 have colors in the spectrum between red and green. The green color indicates desired (smaller) values for all parameters. Namely the colored columns are ROM (flash) & RAM memories, maximum frequency and minimum active current consumption in MCU's *active* mode. The other parameters may occasionally gain importance based on the application (*e.g.* extreme operating temperature).

This is obvious from Table 9 that at the same price window, 32-bit MCU choices offer better features, including current consumption. Apart from this, a 32-bit architecture can host modern embedded operating systems (*e.g.* Linux, Android and Window10-IoT) which in turn offers more featured and robust software environment (*e.g.* networking, event handling, multi-taking and high-level programming). While small MCUs (8-bit) are more common for small applications (without crypto), 32-bit MCUs are more susceptible candidates for future of low-power embedded cryptography, as they consume less power consumption and propose higher features at the same price.

Case study on 8-bit and 32-bit MCUs: There is another aspect of 32-bit MCUs which can tip the balance even more in their favor. Due to wider data-paths, the 32-bit MCUs can process more data than 8-bit or 16-bit ones during the same clock cycles. Therefore, if a well-crafted program can take advantage of the 4-byte computation in a 32-bit MCU, it would have theoretically a performance boost of four times in comparison to a 1-byte computation 8-bit MCUs. This makes energy-per-byte during the computation even smaller.

Moreover, the programming models of different architectures can also affect energy consumption. For example, a limited number of general purpose registers resorts more memory load and storage operations since there are not enough general purpose CPU registers to keep data within the CPU. On the other hand, diversity of machine-level operations (*e.g.* bit manipulation) can make cryptography building blocks faster(*e.g.* bit permutation). Aside from all the above-mentioned differences, cipher structure is also important. For example, some ciphers (*e.g.* `AES`) are byte-oriented ciphers and some others have wider data-block operations (*e.g.* `Speck`). Therefore, we expect to see different performance improvement when a byte-oriented (8-bit) cipher runs rather than a double-word-oriented (32-bit) cipher.

Just as a case study, we compiled `Speck` (double-word-oriented)[241] and `AES` (byte-oriented [242]) on two MCUs: an ARM Cortex-M0 (32-bit) on nRF51822 and an AVR (8-bit) on Arduino Uno. The goal was to observe the resources that each architecture needs to host the algorithms and also the performance that they present. Table 10 presents the results for memory consumption and execution time. The ARM architecture consumes more memory for `AES` cipher but its performance is significantly superior. For the `Speck` case, ARM uses nearly the same RAM, but it needs lower ROM and provides extremely better performance. The improvement over `Speck` mainly comes from the fact that this cipher is an inherently 32-bit cipher and better suits 32-bit

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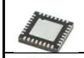
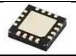
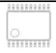
[4] https://mou.sr/2UR6YJX - https://mou.sr/2UOF2Gw - https://mou.sr/2ULVxTM

Table 9. Comparison of MCUs in price range of 1.35 to 1.55 Euros

Image	**Manuf.**	**Data-width**	**Core Family**	**Model**	**Flash**	**RAM**	**ADC Res.**	**Interfaces**	**Maxi. Freq.**	**Temp. °C**	**Operating Voltage**	**Min. Active Current µA/MHz**	**I/O Pins**	**Price** EUR/unit
	Cypress	32-bit	ARM Cortex-M0+	PSoC4100	64k	8k	12 bits	I2C, SPI/UART	48 MHz	-40 +85	1.7V 5.5V	**27**	32/48	**1.35**
	Silicon Lab	32-bit	ARM Cortex-M0+	EFM32TG11	64k	32k	12 bits	CAN, I2C, SPI, UART, USB	48 MHz	-40 +85	1.8V 3.8V	**38**	24	**1.48**
	Microchip	32-bit	ARM Cortex-M23	ATSAML10	16k	4k	12 bits	I2C, SPI, UART, ISO7816, RS-485, LIN	32 MHz	-40 +125	1.62V 3.63V	**22**	25	**1.55**
	Maxim	32-bit	ARM Cortex M4	MAX32660	256k	96k	12 bits	I2C, SPI, UART	96 MHz	-40 +105	1.1V 1.8V	**50**	14	**1.56**
	Microchip	16-bit	PIC24	PIC24F04KL10x	4k	512	NA	I2C, SPI, UART	32 MHz	-40 +85	1.8V 3.6V	**150**		**1.49**
	Texas	16-bit	MSP430	MSP430G2232	2k	256	10 bits	I2C, SPI	16 MHZ	-40 +85	1.8V 3.6V	**220**	10	**1.50**
	Renesas	16-bit	RL78	RL78	8k	768	10 bits	CSI, I2C, UART	24 MHz	-40 +85	1.8V 5.5 V	**45**	18	**1.51**
	ST Micro.	8-bit	STM8	STM8L151C2	4k	1k	12 bits	I2C, SPI, USART	16 MHZ	-40 +85	1.8V 3.6V	**115**	40	**1.50**
	Silicon Labs	8-bit	8051	C8051F818	8k	512	10 bits	I2C, SPI, UART	25 MHz	-55 +125	1.8V 3.6V	**184**	17	**1.50**
	Microchip	8-bit	PIC16	PIC16(L)F18445	14k	1k	12 bits	Serial	32 MHz	-40 +125	2.3V 5.5 V	**112**	18	**1.51**
	Microchip	8-bit	PIC12	PIC12F675	1.75k	64	10 bits	NA	20 MHz	-40 +85	2 V 5.5 V	**45**	6	**1.51**
	ST Micro.	8-bit	ST7	ST7FOXK1	4k	384	10 bits	I2C	8 MHz	-40 +85	4.5 V 5.5 V	**625**	24	**1.51**
	Silicon Labs	8-bit	CIP-51	EFM8LB1	64k	~4k	14 bits	Serial	72 MHz	-40 +105	2.2 V 3.6V	**179**	29	**1.21**
	Microchip	8-bit	AVR	ATmega168PA	16k	1k	10 bits	2-Wire, SPI, USART	20 MHz	-40 +85	1.8V 5.5 V	**325**	23	**1.53**

ARM architecture. It means that each 32-bit operation on ARM is equivalent of several 8-bit operation on AVR. AES intrinsically is an 8-bit cipher. Therefore, the performance improvement is not the same as for Speck.

Nevertheless, this study shows that 32-bit architectures generally outperform 8-bit architectures in price, energy and performance.

Table 10. Comparing a 8-bit and a 32-bit MCUs with Speck and AES encryption

Architecture	RAM		ROM		Execution time	
Algo.	AES	Speck	AES	Speck	AES	Speck
AVR	398	227	3329	656	61102	23354
ARM	596	240	4228	220	6771	619
Improvement	-%50	-%5	-%27	%66	%89	%97

4.1.2 *MCU operating frequency.*

MCUs present different operating frequencies and an IoT designer wants to select one with the lowest energy consumption. Here we present a case study on our nRF51822 device and short discussion about choosing the right frequency.

Referring to the nRF51822 specification[243], we find that the typical current consumption of the entire device are 520 µA and 560 µA when it works on its two intended frequencies: 16Mhz and 32Mhz, respectively. This means that the power consumption is higher at 32Mhz as is normally expected. But we should notice that for energy consumption, which is the aim of this paper, both current and time are determining factors. We can simply assume that an MCU working on 32MHz will finish its cryptography task in half of amount of time that it takes if it works on 16MHz. Therefore we can state that the *per-bit* energy consumption ratio of a task on 16MHz and 32MHz is 520 µA to 560/2 µA. This means that energy consumption at 32MHz is about %53 lower than at 16MHz.In other words, an MCU at a higher frequency can finish its task sooner and go to a sleep mode (with current consumption of order of nA) in order to save the energy.

As a conclusion, setting up an MCU to work on higher frequency along with using power management (sleep mode) can effectively reduce the energy consumption.

4.2 Communication Sub-domain

Here we shortly present a study on two parameters regarding the communication in IoT devices: *data transmission rates* and *Transmission Signal Strength*.

4.2.1 Data Transmission Rates. The per-bit energy consumption is lower for higher communication data rates. For instance, current consumption for data rates 250Kbps, 1Mbps and 2Mbps is 12.6, 13.0 and 13.4 mA, respectively[243]. The data rate of 2Mbps is twice faster than 1Mbps and eight times faster than 250Kbps. This means that the per-bit current consumption are respectively, 50, 13 and 6.7 µA for 250Kbps, 1Mbps and 2Mbps, respectively. Hence, its per-bit energy consumption is roughly two and eight times lower than the two other data rates. This implies using higher data rates for data transmission.

4.2.2 Transmission Signal Strength. Lower signal strength consumes less energy, but at the expense of quality of service . Therefore, an embedded system designer may decide to trade Quality of Service (QoS) with lower energy consumption. However, calculating the overall power reduction is not straightforward and depends on the application, the presence of other devices at the same frequency and the distance between the peers [244, 245]. For example, a lower signal strength reduces the current consumption but it decreases the signal to noise ratio (SNR) which consequently can increase the rate of data transmission error and extra energy for packet re-transmission[246]. This is beyond the scope of this paper and we only study the effect of simple signal strength variations and omit other influential parameters like distance and environmental noises.

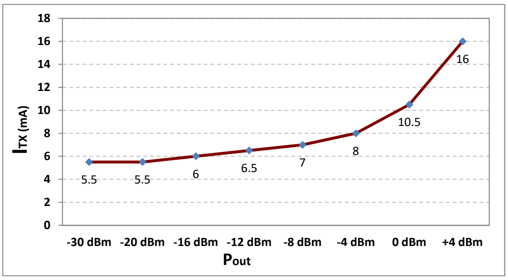


Fig. 2. Effect of transmission signal power on the MCU current[243]

Figure 2 illustrates the relation between transmission power and the device's current[243]. We observe that the relation is not linear and as we decrease the transmission power, the energy reduction gain will be less significant. And after -20 dBm, there is no energy gain for transmission power reduction.

5 CRYPTOGRAPHY DOMAIN

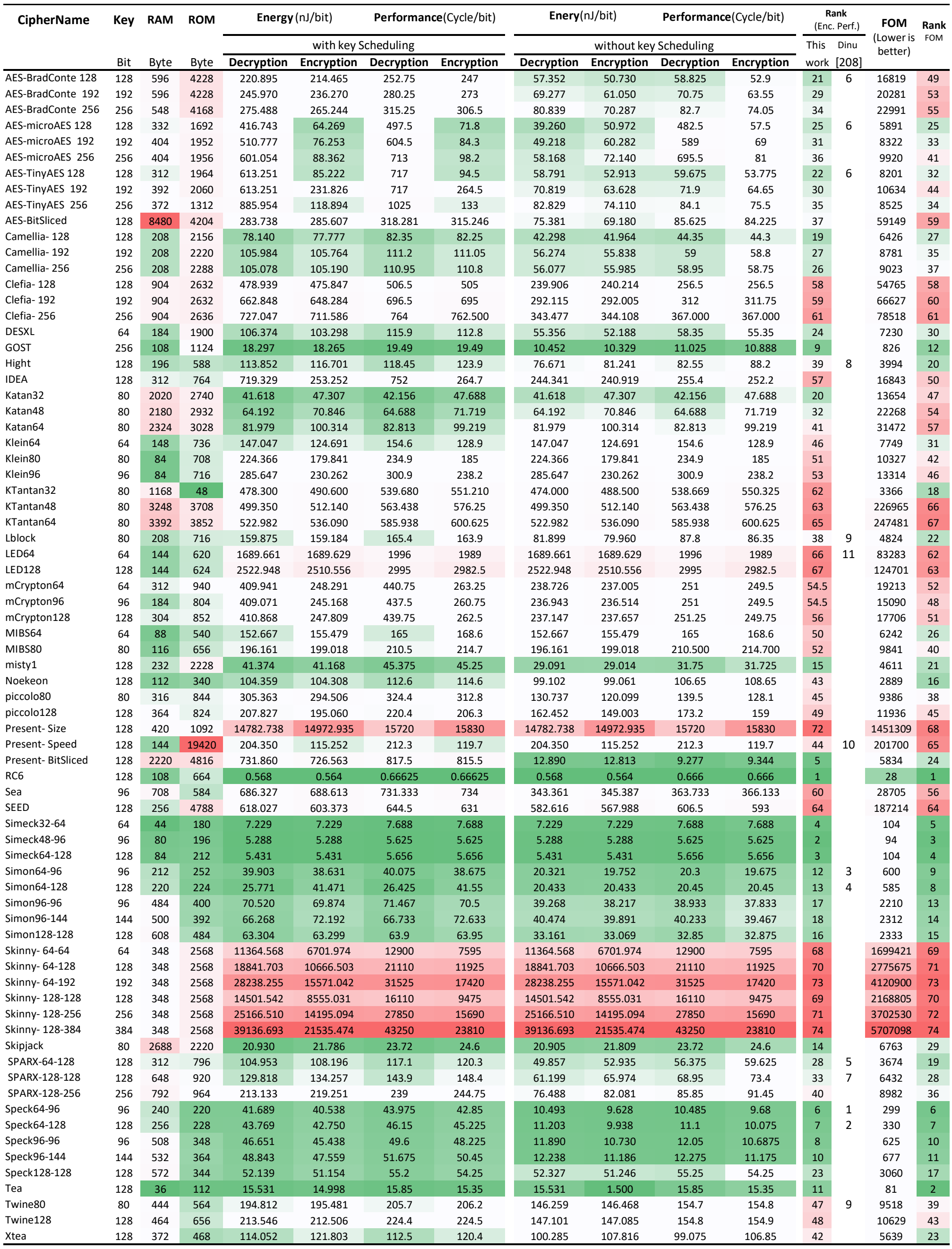
This domain is divided into three sub-domains: "confidentiality", "authentication" and "key exchange" as described in Section 2. It should be noted for all the ciphers, we omitted any initialization phase for this comparison, because any initialization could be carried out offline and out of the device to save energy. Here we present our benchmarking results on each sub-domain separately:

5.1 Confidentiality

5.1.1 Results for Symmetric Encryption. Table 11 presents the benchmarking results. It also includes memory consumption for the sake of completeness. The energy and performance are "per-bit" results for encryption and decryption executions. This provides normalized and comparable results. As the majority of the ciphers require a "Key-Scheduling" phase to generate round keys prior to the encryption or decryption, we provided the results for ciphers "with" and "without" their key scheduling phase in two different columns. For those ciphers which do not have key scheduling (*e.g.* `TEA`) we repeated the same results for both columns. Normally, the results without key scheduling matters more in our energy optimization study, as the key scheduling runs only when the old key is revoked and a new key is renewal. Also, in separate columns, we ranked ciphers based on their encryption performance along with the common ciphers in [208]. We chose this work for comparison because they used ARM Cortex-M4 which is the closest to our chosen MCU architecture. The ranking from [208] is almost the same except for few ciphers (`HIGHT`& `LBlock`) with close performance record.

Low-energy choices: Table 11 is colored in a spectrum from green to red, which green cells have desirable values. In this table, we can observe that `Simon`, `Speck` and `Simeck` families show acceptable energy/performance for all key and block sizes, while `Simeck` has significantly better FOM, after that `Speck`is slightly more efficient in terms of memory than `Simon`. Another two compact, fast and low energy ciphers are `TEA` and `RC6` which have the best FOMs. `GOST` also has an acceptable energy performance profile but its memory usage is significant. The next comparable families are `Camellia` and `AES`.

Table 11. Benchmark results for block ciphers on nRF51822 (ARM Cortex-M0)



CipherName	**Key**	**RAM**	**ROM**	**Energy** (nJ/bit)		**Performance**(Cycle/bit)		**Enery**(nJ/bit)		**Performance**(Cycle/bit)		**Rank** (Enc. Perf.)		**FOM** (Lower is better)	**Rank** FOM
				with key Scheduling				without key Scheduling				This work	Dinu [208]		
	Bit	Byte	Byte	**Decryption**	**Encryption**	**Decryption**	**Encryption**	**Decryption**	**Encryption**	**Decryption**	**Encryption**				
AES-BradConte 128	128	596	4228	220.895	214.465	252.75	247	57.352	50.730	58.825	52.9	21	6	16819	49
AES-BradConte 192	192	596	4228	245.970	236.270	280.25	273	69.277	61.050	70.75	63.55	29		20281	53
AES-BradConte 256	256	548	4168	275.488	265.244	315.25	306.5	80.839	70.287	82.7	74.05	34		22991	55
AES-microAES 128	128	332	1692	416.743	64.269	497.5	71.8	39.260	50.972	482.5	57.5	25	6	5891	25
AES-microAES 192	192	404	1952	510.777	76.253	604.5	84.3	49.218	60.282	589	69	31		8322	33
AES-microAES 256	256	404	1956	601.054	88.362	713	98.2	58.168	72.140	695.5	81	36		9920	41
AES-TinyAES 128	128	312	1964	613.251	85.222	717	94.5	58.791	52.913	59.675	53.775	22	6	8201	32
AES-TinyAES 192	192	392	2060	613.251	231.826	717	264.5	70.819	63.628	71.9	64.65	30		10634	44
AES-TinyAES 256	256	372	1312	885.954	118.894	1025	133	82.829	74.110	84.1	75.5	35		8525	34
AES-BitSliced	128	8480	4204	283.738	285.607	318.281	315.246	75.381	69.180	85.625	84.225	37		59149	59
Camellia- 128	128	208	2156	78.140	77.777	82.35	82.25	42.298	41.964	44.35	44.3	19		6426	27
Camellia- 192	192	208	2220	105.984	105.764	111.2	111.05	56.274	55.838	59	58.8	27		8781	35
Camellia- 256	256	208	2288	105.078	105.190	110.95	110.8	56.077	55.985	58.95	58.75	26		9023	37
Clefia- 128	128	904	2632	478.939	475.847	506.5	505	239.906	240.214	256.5	256.5	58		54765	58
Clefia- 192	192	904	2632	662.848	648.284	696.5	695	292.115	292.005	312	311.75	59		66627	60
Clefia- 256	256	904	2636	727.047	711.586	764	762.500	343.477	344.108	367.000	367.000	61		78518	61
DESXL	64	184	1900	106.374	103.298	115.9	112.8	55.356	52.188	58.35	55.35	24		7230	30
GOST	256	108	1124	18.297	18.265	19.49	19.49	10.452	10.329	11.025	10.888	9		826	12
Hight	128	196	588	113.852	116.701	118.45	123.9	76.671	81.241	82.55	88.2	39	8	3994	20
IDEA	128	312	764	719.329	253.252	752	264.7	244.341	240.919	255.4	252.2	57		16843	50
Katan32	80	2020	2740	41.618	47.307	42.156	47.688	41.618	47.307	42.156	47.688	20		13654	47
Katan48	80	2180	2932	64.192	70.846	64.688	71.719	64.192	70.846	64.688	71.719	32		22268	54
Katan64	80	2324	3028	81.979	100.314	82.813	99.219	81.979	100.314	82.813	99.219	41		31472	57
Klein64	64	148	736	147.047	124.691	154.6	128.9	147.047	124.691	154.6	128.9	46		7749	31
Klein80	80	84	708	224.366	179.841	234.9	185	224.366	179.841	234.9	185	51		10327	42
Klein96	96	84	716	285.647	230.262	300.9	238.2	285.647	230.262	300.9	238.2	53		13314	46
KTantan32	80	1168	48	478.300	490.600	539.680	551.210	474.000	488.500	538.669	550.325	62		3366	18
KTantan48	80	3248	3708	499.350	512.140	563.438	576.25	499.350	512.140	563.438	576.25	63		226965	66
KTantan64	80	3392	3852	522.982	536.090	585.938	600.625	522.982	536.090	585.938	600.625	65		247481	67
Lblock	80	208	716	159.875	159.184	165.4	163.9	81.899	79.960	87.8	86.35	38	9	4824	22
LED64	64	144	620	1689.661	1689.629	1996	1989	1689.661	1689.629	1996	1989	66	11	83283	62
LED128	128	144	624	2522.948	2510.556	2995	2982.5	2522.948	2510.556	2995	2982.5	67		124701	63
mCrypton64	64	312	940	409.941	248.291	440.75	263.25	238.726	237.005	251	249.5	54.5		19213	52
mCrypton96	96	184	804	409.071	245.168	437.5	260.75	236.943	236.514	251	249.5	54.5		15090	48
mCrypton128	128	304	852	410.868	247.809	439.75	262.5	237.147	237.657	251.25	249.75	56		17706	51
MIBS64	64	88	540	152.667	155.479	165	168.6	152.667	155.479	165	168.6	50		6242	26
MIBS80	80	116	656	196.161	199.018	210.5	214.7	196.161	199.018	210.500	214.700	52		9841	40
misty1	128	232	2228	41.374	41.168	45.375	45.25	29.091	29.014	31.75	31.725	15		4611	21
Noekeon	128	112	340	104.359	104.308	112.6	114.6	99.102	99.061	106.65	108.65	43		2889	16
piccolo80	80	316	844	305.363	294.506	324.4	312.8	130.737	120.099	139.5	128.1	45		9386	38
piccolo128	128	364	824	207.827	195.060	220.4	206.3	162.452	149.003	173.2	159	49		11936	45
Present- Size	128	420	1092	14782.738	14972.935	15720	15830	14782.738	14972.935	15720	15830	72		1451309	68
Present- Speed	128	144	19420	204.350	115.252	212.3	119.7	204.350	115.252	212.3	119.7	44	10	201700	65
Present- BitSliced	128	2220	4816	731.860	726.563	817.5	815.5	12.890	12.813	9.277	9.344	5		5834	24
RC6	128	108	664	0.568	0.564	0.66625	0.66625	0.568	0.564	0.666	0.666	1		28	1
Sea	96	708	584	686.327	688.613	731.333	734	343.361	345.387	363.733	366.133	60		28705	56
SEED	128	256	4788	618.027	603.373	644.5	631	582.616	567.988	606.5	593	64		187214	64
Simeck32-64	64	44	180	7.229	7.229	7.688	7.688	7.229	7.229	7.688	7.688	4		104	5
Simeck48-96	96	80	196	5.288	5.288	5.625	5.625	5.288	5.288	5.625	5.625	2		94	3
Simeck64-128	128	84	212	5.431	5.431	5.656	5.656	5.431	5.431	5.656	5.656	3		104	4
Simon64-96	96	212	252	39.903	38.631	40.075	38.675	20.321	19.752	20.3	19.675	12	3	600	9
Simon64-128	128	220	224	25.771	41.471	26.425	41.55	20.433	20.433	20.45	20.45	13	4	585	8
Simon96-96	96	484	400	70.520	69.874	71.467	70.5	39.268	38.217	38.933	37.833	17		2210	13
Simon96-144	144	500	392	66.268	72.192	66.733	72.633	40.474	39.891	40.233	39.467	18		2312	14
Simon128-128	128	608	484	63.304	63.299	63.9	63.95	33.161	33.069	32.85	32.875	16		2333	15
Skinny- 64-64	64	348	2568	11364.568	6701.974	12900	7595	11364.568	6701.974	12900	7595	68		1699421	69
Skinny- 64-128	128	348	2568	18841.703	10666.503	21110	11925	18841.703	10666.503	21110	11925	70		2775675	71
Skinny- 64-192	192	348	2568	28238.255	15571.042	31525	17420	28238.255	15571.042	31525	17420	73		4120900	73
Skinny- 128-128	128	348	2568	14501.542	8555.031	16110	9475	14501.542	8555.031	16110	9475	69		2168805	70
Skinny- 128-256	256	348	2568	25166.510	14195.094	27850	15690	25166.510	14195.094	27850	15690	71		3702530	72
Skinny- 128-384	384	348	2568	39136.693	21535.474	43250	23810	39136.693	21535.474	43250	23810	74		5707098	74
Skipjack	80	2688	2220	20.930	21.786	23.72	24.6	20.905	21.809	23.72	24.6	14		6763	29
SPARX-64-128	128	312	796	104.953	108.196	117.1	120.3	49.857	52.935	56.375	59.625	28	5	3674	19
SPARX-128-128	128	648	920	129.818	134.257	143.9	148.4	61.199	65.974	68.95	73.4	33	7	6432	28
SPARX-128-256	256	792	964	213.133	219.251	239	244.75	76.488	82.081	85.85	91.45	40		8982	36
Speck64-96	96	240	220	41.689	40.538	43.975	42.85	10.493	9.628	10.485	9.68	6	1	299	6
Speck64-128	128	256	228	43.769	42.750	46.15	45.225	11.203	9.938	11.1	10.075	7	2	330	7
Speck96-96	96	508	348	46.651	45.438	49.6	48.225	11.890	10.730	12.05	10.6875	8		625	10
Speck96-144	144	532	364	48.843	47.559	51.675	50.45	12.238	11.186	12.275	11.175	10		677	11
Speck128-128	128	572	344	52.139	51.154	55.2	54.25	52.327	51.246	55.25	54.25	23		3060	17
Tea	128	36	112	15.531	14.998	15.85	15.35	15.531	1.500	15.85	15.35	11		81	2
Twine80	80	444	564	194.812	195.481	205.7	206.2	146.259	146.468	154.7	154.8	47	9	9518	39
Twine128	128	464	656	213.546	212.506	224.4	224.5	147.101	147.085	154.8	154.9	48		10629	43
Xtea	128	372	468	114.052	121.803	112.5	120.4	100.285	107.816	99.075	106.85	42		5639	23

5.1.2 Results for Stream Ciphers. Table 12 presents benchmarking results for the same parameters described for block ciphers. According to the results, optimized version of `HC128` has the lowest energy consumption but `Trivium`, `Rabbit` and `Mikcey-v2` have the best FOMs.

Table 12. Benchmark results for stream ciphers on nRF51822 (ARM Cortex-M0)

CipherName	**Key**	**RAM**	**ROM**	**Energy**	**Performance**	**Rank** Perf.	**FOM** (Lower is better)	**Rank** FOM
	Bit	Byte	Byte	nJ/bit	Cycle/bit			
Chacha	128	552	1256	5.68	5.94	8	10278	4
F-FCSR-16	128	580	1116	25.36	26.43	11	43018	9
F-FCSR-H	80	452	840	29.63	31.19	12	38287	7
Grain-v1	80	1124	1680	3314.24	3671.88	14	9293115	15
Grain128	128	740	608	5003.54	5453.13	15	6744776	14
HC128	128	9564	848	3.86	4.33	2	40139	8
HC128 32-bit speed	128	6368	4952	1.83	1.94	1	20729	6
HC256	256	18820	756	9.72	10.87	10	190356	12
HC256 32-bit speed	256	8704	6344	5.40	5.75	7	81190	11
Mickey v2	80	688	964	4.83	5.08	4	7971	3
Rabbit	128	472	724	5.14	5.22	6	6144	2
Salsa20	256	528	1048	9.61	9.57	9	15149	5
Sosemanuk	40	940	12864	4.83	5.08	4	66607	10
Snow3g	128	288	1980	1243.58	1442.50	13	2820445	13
Trivium	80	444	752	4.43	4.50	3	5299	1

5.2 Authentication and Integrity

Authentication and Integrity sub-domains utilize of 1)AEAD 2)Hash Functions 2)MAC 3)Digital Signature. Here are the results for each category.

5.2.1 Results for AEAD mechanism. Table 13 illustrates the results for AEAD algorithms. The columns contain the results when the algorithms provide "confidentiality and authentication" services which entails both encryption and authentication and also the results for "authentication-only" service which provides only authenticity.

Some of the ciphers have different implementations available and can be distinguished by their names. For example, `Deoxys2` has a reference and a table-based implementations. `MORUS` and `ACORN` have optimized versions along with their reference codes. Moreover, ciphers have one or two numbers after their names. The first number indicates the key length and the second (if any) indicates the internal parameters of the cipher (commonly state or block size). Both numbers are necessary to distinguish the code among different implementations in the code repository. Exceptionally for `OCB`, the second number indicates the authentication tag size.

On average, we can see that `AEGIS`, `ACORN`, `OCB` and `MORUS` and families have the lowest energy consumption. Among them, for `AEGIS` and `ACORN`, the energy consumption on encryption and decryption are nearly the same which makes them better choices for low-power crypto.

From another perspective, we expected to observe energy reduction for the "authentication-only" service, as it does not provide encryption. But, this is not always the case, specifically for our low-power choices, `ACORN`, `AEGIS` and `OCB`, the energy consumption is the same with or without the confidentiality service. This is due to the fact that for these AEAD algorithms, the authentication and confidentiality services both utilize the same cryptographic operations. Therefore, excluding one service does not yield in less operations. In conclusion, while we utilize low-power AEAD, switching from authenticated-encryption service to authentication-only is futile and does not yield in significant energy reduction.

Table 13. Benchmark results for AEAD ciphers on nRF51822 (ARM Cortex-M0)

CipherName	**Key**	**RAM**	**ROM**	**Energy** (nJ/bit)		**Performance** (Cycle/bit)		**Rank**	**Energy** (nJ/bit)		**Performance** (Cycle/bit)		**Rank**	**FOM** (Lower is better)
				Confidentiality + Authentication				Enc.	**Authentication-only**				Enc.	
	Bit	Byte	Byte	**Enc.**	**Dec.**	**Enc.**	**Dec.**	Perf.	**Enc.**	**Dec.**	**Enc.**	**Dec.**	Perf.	
ACORN128-v3-Optimized	128	824	3492	40.03	41.01	42.63	43.19	12	40.39	39.92	42.38	42.34	14	349755
Aegis128	128	812	6312	20.99	21.38	23.06	23.33	2	21.23	20.94	23.29	23.00	2	301840
Aegis256	256	892	6396	30.00	30.43	32.75	33.03	5	30.32	30.32	33.06	33.06	7	440427
Ascon128-128	128	840	3788	149.36	238.64	161.88	271.25	20	154.46	156.30	167.13	169.63	20	1795666
Deoxysii128-141-Ref	128	1200	17116	401.91	402.37	450.00	450.31	21	212.54	212.71	238.75	238.50	21	14731183
Deoxysii128-141-Table	128	1432	26788	57.50	55.88	61.41	59.34	18	34.54	34.05	37.19	36.88	10	3199714
Deoxysii256-141-Ref	256	1232	17116	636.08	633.68	717.19	717.81	22	338.39	338.52	380.00	380.31	22	23297534
Deoxysii256-141-Table	256	1464	26788	141.57	142.86	154.63	155.63	19	114.41	113.92	129.69	129.50	19	8035632
Morus128-1280v2- 64-Opt.	128	1072	8196	49.63	101.79	50.25	103.06	15	49.80	101.79	50.38	50.31	15	1403390
Morus128-1280v2- Ref	128	1072	8196	49.86	102.09	50.31	103.13	16	49.86	49.49	50.38	50.22	15	1408296
Morus256-1280v2- 64-Opt.	256	1088	8184	49.54	101.79	50.06	102.75	14	99.11	49.13	100.56	50.00	17	1403116
Morus256-1280v2-Ref	256	1088	4228	50.03	101.71	50.34	103.19	17	99.16	49.38	100.94	50.28	18	806621
Morus128-640v2	128	808	2424	21.53	45.30	21.98	46.38	1	21.53	21.53	21.98	21.78	1	215975
OCB-128v1	128	1648	12536	27.87	27.16	28.26	27.60	3	27.13	27.31	27.50	27.70	3	780493
OCB-64v1	128	1648	12536	32.83	34.73	33.71	35.71	6	31.20	33.98	31.95	34.75	5	958207
OCB-96v1	128	1152	17628	32.83	34.89	33.71	35.81	6	31.19	33.69	31.95	34.80	5	1271713
OCB-128v1	192	1656	12536	30.94	30.38	31.71	31.01	4	30.68	30.84	31.10	31.25	4	870259
OCB-64v1	192	1656	12536	36.11	38.31	37.11	39.41	9	37.64	37.64	38.55	38.55	11	1056132
OCB-96v1	192	1160	17628	36.17	38.41	37.11	39.51	9	34.57	37.65	35.40	38.60	9	1401074
OCB-128v1	256	1664	12544	35.51	34.36	35.91	35.21	8	35.28	35.17	35.30	35.45	8	992714
OCB-64v1	256	1664	12544	40.42	43.14	41.21	44.11	11	38.79	42.79	39.50	43.35	12	1187135
OCB-96v1	256	1168	17636	43.23	43.23	44.21	44.21	13	38.72	42.49	39.50	43.40	12	1625957

Table 14. Benchmark results for hash ciphers

CipherName	Input	Key/IV	Digest	RAM	ROM	Energy	Perform.	Rank Perf.	FOM (Lower is	Rank FOM
	Bytes	Bit	Bit	Bytes	Bytes	nJ/bit	Cycle/bit			
Blake256	1024	512	256	1448	2304	22.81	23.00	12	85594	3
Blake2b	1024	512	512	2168	16188	43.73	47.50	20	802626	17
Blake2s	1024	256	512	1736	8128	13.52	14.40	7	133384	8
Blake32	1024	512	256	1448	2404	17.09	17.38	9	65835	2
Blake512	1024	512	512	1904	4184	29.08	28.75	16	177015	11
Blake64	1024	512	512	1904	4184	26.02	25.63	14	158402	9
Grostl256	1024	512	256	1244	23956	13.18	13.23	1	332236	14
Grostl512	1024	512	512	1244	23956	13.16	13.23	2	331670	13
JH224	1024	512	224	1628	5084	13.61	13.29	3	91321	4
JH256	1024	512	256	1660	5084	13.62	13.29	3	91842	5
JH384	1024	512	384	1788	5084	13.65	13.30	5	93823	6
JH512	1024	512	512	1916	5084	13.52	13.30	6	94646	7
Keccak1024	1024	512	1024	2944	28912	89.91	92.54	22	2864300	22
Keccak256	1024	512	256	2176	28908	26.78	27.55	15	832520	18
Keccak448	1024	512	448	2368	28908	36.00	37.09	19	1125862	20
Keccak512	1024	512	512	2432	28912	35.79	36.91	18	1121715	19
Keccak768	1024	512	768	2688	28912	54.17	55.59	21	1711869	21
Skein1024	1024	1024	1024	2548	5932	30.12	30.18	17	255394	12
Skein256	1024	256	256	1764	7956	18.03	18.23	10	175300	10
Skein512	1024	512	256	1980	15900	22.69	22.96	11	405693	15
Skein512	1024	512	512	1980	15900	22.69	23.11	13	405723	16
Photon-80	1024	200	80	1352	3888	1780.73	2015.63	23	9331046	23
Photon-128	1024	288	128	1360	3916	3719.41	4171.88	27	19623592	27
Photon-160	1024	392	160	1376	3936	2603.19	2889.06	24	13828133	24
Photon-192	1024	392	192	1376	3936	23797.44	26453.13	29	126412026	29
Photon-224	1024	512	224	1384	3860	3032.83	3410.16	26	15904165	26
Photon-256	1024	288	256	1360	4068	2766.03	3107.81	25	15014030	25
Quark	1024	384	384	2828	1516	7078.69	7085.94	28	30749814	28
SipHash	1024	128	64	1152	2192	14.01	15.50	8	46854	1
Spongent	1024	128	128	1212	1384	79604.63	86328.13	30	206653631	30

5.2.2 Results for Hash Functions on nRF51822 (ARM Cortex-M0). Table 14 presents the results for the SHA3 competition finalists. Among them, `Grøstl`, `JH` and `BLAKE` have the lowest energy consumption, respectively; `Keccak` as the SHA3 winner consumes about two or three times more energy. `Sip-Hash` and `BLAKE` family have the best FOM because of their small memory footprint, followed by `JH` family stands in third place.

5.2.3 Results for MAC structures. Table 15 presents the benchmarking results for the message authentication codes (MAC). Among them, the first four mechanisms (`CBC`, `OMAC`, `PMAC` and `XCBC`) are based on symmetric ciphers and use block encryption (`AES`) in order to produce authentication tag. The last two, namely, `BLAKE2` and `HMAC-SHA1` are based on the hash functions. The first one uses `BLAKE` and later uses `SHA1` as their hash function.

`HMAC-SHA1` has the lowest energy consumption among all mechanisms; But if we want to choose a cipher-based MAC mechanism, `OMAC` is the most effective low-energy structure.

5.2.4 Results for Signature structures. Now, we present the benchmarking results for asymmetric cryptography services. Table 16 shows the results for authentication service using digital signature. For this purpose, we signed a fixed amount of plaintext using all the four digital signature schemes, namely, two prime factorization based schemes (`DSA` & `RSA-PSS`) and two elliptic curve based schemes (`Ed25519` & `ECDSA`). In order to compare algorithms at the same order of security strength, based on NIST recommendations for key lengths [247], we can choose `DSA` and `RSA-PSS` with key length of 2048 to be compared with `ECDSA` and `Ed25519` at the key length of 256. In comparison, `RSA-PSS` is the most efficient for generating and `DSA` for verifying them. The prime factorization-based schemes (`RSA-PSS` and `DSA`) show different performance and energy consumption on singing and verification, while elliptic-curve based schemes (`ECDSA` and `Ed25519`) have nearly the same numbers for both functions. It is worth to mention that there would be many parameters that can tip the balance in favor of each scheme if we go more in depth of their constructing mathematics [248, 249]. For example, their internal random number generators can affect the time needed for modular exponentiation of the generated numbers. However, this report was an example of what a developer has available in her hand when she wants to apply cryptography using existing libraries and available components without the need to modify the library for optimization.

Table 15. Benchmark results for MAC structures on nRF51822 (ARM Cortex-M0)

CipherName	Key	RAM	ROM	Power (nJ/bit)	Perform. (Cycle/bit)	FOM (Lower is better)
CBC-MAC-AES	128	1224	3984	52.314	53.477	272453
OMAC-CMAC-AES	128	4416	23644	18.089	18.047	507585
PMAC-AES	128	4416	24436	24.455	24.906	705572
XCBC-MAC-AES	128	4416	23520	27.173	27.875	759110
BLAKE2-MAC	128	2472	24876	19.943	19.703	545398
HMAC-SHA1	128	1376	4776	11.771	12.234	72415

Table 16. Benchmark results for signature algorithms on nRF51822 (ARM Cortex-M0)

Cipher	Key	Energy (nJ/bit)	Perf. (Cycle/bit)	Energy (nJ/bit)	Perf. (Cycle/bit)
	Bit	Signature		Verify	
DSA-1024	1024	183245.12	203688	366139.06	406125
DSA-2048	2048	666758.33	741750	1425011.07	1486250
ECDSA-256	256	503939.71	543125	501457.29	544875
ECDSA-384	348	1184861.98	1261875	1179392.58	1263125
ECDSA-512	512	2696798.18	2880625	2736593.75	2880625
ED25519-256	256	601686.7	640000	628210.16	640000
RSA-PSS-1024	1024	434597.40	465750	37937.06	42250
RSA-PSS-2048	2048	2624384.11	2767500	146531.51	154438

Table 17. Benchmark results for key generation mechanisms on nRF51822 (ARM Cortex-M0)

Cipher	Key	Energy	Performance
	Bit	nJ/bit	Cycle/bit
CURVE25519	1024	69908.43	75469
DH-1952	2048	41317.45	45369

5.3 Results for Key Generation Mechanisms

Finally, Table 17 presents results for the key generation schemes. It is obvious that Diffie-Hellman (DH) has lower energy consumption and better performance than Curve25519. The reason mainly lies on the fact that modular exponentiation in DH runs faster on MCUs than elliptic curve mathematics. Diffie-Hellman is faster than Curve25519 by one order of magnitude.

6 OVERALL COMPARISON AND A CASE STUDY

Now, we try to provide a big picture over the obtained results which are presented in this paper. Before that, we exclude digital signature and key establishment services from our overview, because their scale is too large to fit in a figure with the other crypto constructions. Regarding the tremendous amount of energy needed for asymmetric cryptography, we assume that a system designer decides not to use digital signature for each message transmission in her ultra-low-power system, and instead, she uses MAC or AEAD for authentication. She may only decide to use it for authentication in symmetric session key exchange. Key establishment in an embedded system can be necessary if the crypto key is compromised or its life-time exceeds. This is assumed an extremely rare event in comparison to the device lifetime.

Figure 3 provides the intended picture. It contains per-bit energy consumption of the crypto algorithms and communication modes on the same scale. The cryptography computation part includes symmetric and stream ciphers, hash functions, MAC mechanisms and AEAD structures. In order to have a better image, we excluded the ciphers with more than 100 nJ/bit energy consumption. The results are presented for different key sizes or for different digest sizes (only for hash functions). Some points in this figure are connected together with a line. They indicate the same cipher or structures with different key lengths. The communication part includes the effect of signal strength on energy consumption for different bandwidths.

The first obvious point is the comparison of computation and communication in the per-bit energy consumption. Here we should refer that roughly ten years ago, the energy consumed by the communication part of an embedded system was three orders of magnitude larger than the energy consumed by the cryptography computation part[250]. In other words, the communication energy would have overshadowed that of the computation. Therefore, ten years ago, optimizing cryptography was important only for the sake of performance, rather than energy consumption. But nowadays, due to the emergence of ultra-low-energy communication technologies, optimization on computation energy is as important as the communication.

The next point is about the energy consumption for confidentiality. Stream ciphers were previously known as the faster and simpler structures for data encryption, but some symmetric ciphers exist which their energy and performance can successfully scale with wider data-path (32-bit) MCUs (*e.g.* `Simeck`, `RC6` and `TEA`) and consequently their energy consummation is comparable with stream ciphers.

It should be noted that we are not taking their reported attacks into the consideration. A low-energy cipher (like `TEA`) may be prone to some severe attacks which can cross it out from the list.

Finally, for the authentication service, it seems that conventional MAC mechanisms are still efficient in comparison to the new AEAD mechanisms. Another point about MAC functions is their internal symmetric functions. There are other low-energy symmetric ciphers discussed in this paper which could substitute `AES` in order to have considerably lower energy consumption. For instance, if we apply `Simeck` instead of `AES` in the `OMAC` construction, we expect to have significant power reduction. In conclusion, although AEAD are newer ciphers intended to replace the old authenticated encryption modes (*e.g.* GCM) on different aspects (including security), but from the energy consumption's point of view, conventional MAC constructions still have advantages.

6.1 A Case Study: An Energy Harvested Medical Implant

In this part, through a case study, we explain how the results in this paper can be used in designing security for power-constrained embedded systems. In this case study, a battery-less Implantable Medical Device (IMD) is powered by a variable energy source. IMDs are Cyber-Physical systems which are surgically implanted inside an animal's or human's body in order to monitor physiological parameters and perform therapeutic functions. These *in vivo* devices allow physicians to perform diagnosis, prognosis and biological investigations. This is an appropriate energy optimization scenario because we are dealing with a safety-critical device which requires strict energy provision in order to last for a long period of time in the patient's body.

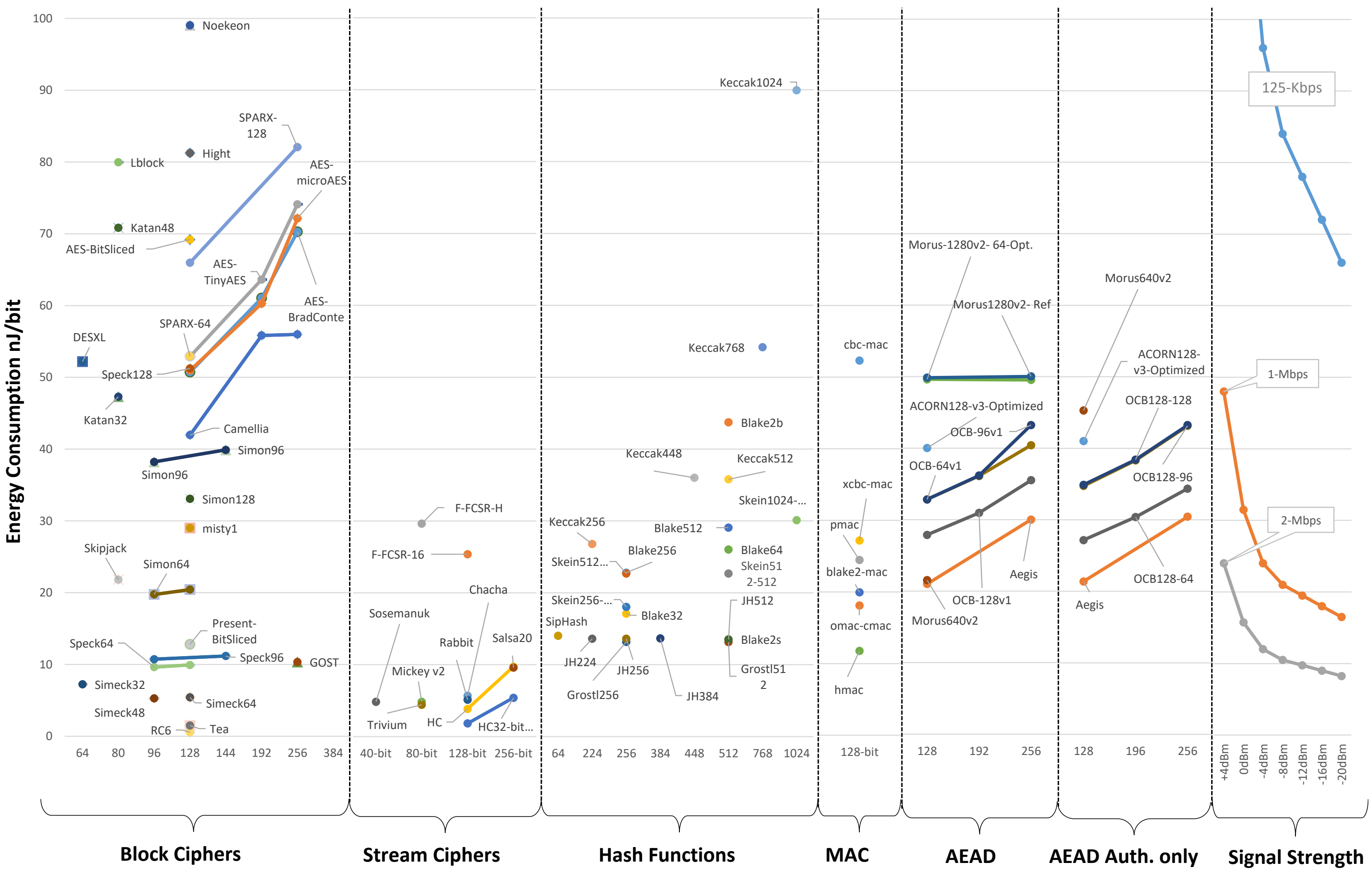


Fig. 3. Overall comparison of ciphers

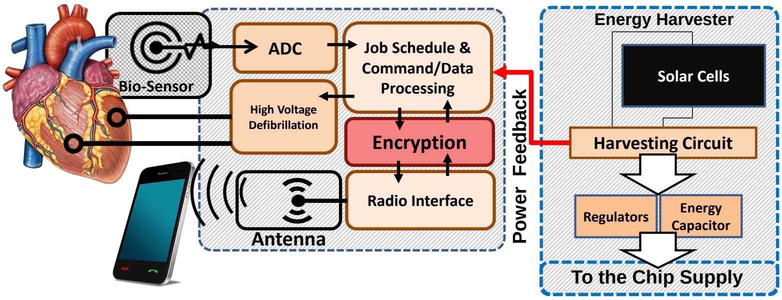


Fig. 4. Block diagram of an energy-harvested Implantable Cardioverter-Defibrillator (ICD)

For the IMD case selection, we assume an energy-harvested implantable cardioverter-defibrillator (ICD). ICD is an electrical impulse generator that is implanted into a patient's body who suffers from ventricular fibrillation and ventricular tachycardia. The goal is to detect cardiac arrhythmia and correct it by delivering a jolt of electricity. The device can send the health status and alarms to a base station near the patient's body (*e.g.* a cell phone). Figure-4 illustrates the block diagram of the energy-harvested ICD which is inspired from the device introduced in [251]. We assume that a periodic task, $T_{sampling}$, samples the patient's heart beats using the bio-sensor (left side of the Figure-4) and then encrypts and transmits the samples to a cell phone within a time interval. In the case of detecting cardiac arrhythmia, another aperiodic task $T_{defibrillation}$ should be instantiated in order to correct the heart beat using the "High Voltage Defibrillation" part.

In order to have a variable energy source, we assume that the ICD is powered by the energy which is harvested from the patient's body or the environment. We decided to use a *solar-powered* generator model. Recent studies shows the feasibility of implanting solar cells under the human skin and utilize it to drive a battery-less ICD [252]. The harvested energy is enough to drive the ICD even in-door and energy buffers allow to survive some darkness periods. Finally, for the sake of reliability, a back-up battery can guarantee the operation in rare and unexpected long darkness experience. Figure-4, in the right side, has a solar generator device which supplies the ICD with the energy harvested from the ambient light. We used the device characterizations of an under-skin solar-powered generator studied in [252]. This device featured a 4.6 cm^2 solar module which can generate approx. 9029 μW (1963 $\mu W/cm^2$) when the patient's skin is exposed the the full sunlight and 947 μW (206 $\mu W/cm^2$) when patient is in outdoor shadow.

Some extra assumptions are as follows: we study only the periodic task $T_{sampling}$ comprised of "heart beat sampling by ADC", "encryption" the samples and "transmission" to the external device. Likewise, $R_{sampling}$ indicates data throughput and $E_{sampling}$ indicates per-bit energy consumption of the periodic task $T_{sampling}$. We show the harvested power from the solar cells by $P_{harvest}$.For simplicity, energy consumption of the other components are assumed constant and negligible, including the bio-sensor and the *aperiodic* task $T_{defibrillation}$.

Under the previously mentioned assumptions, we study a possible design-time scenario. A designer wants to provide secure communication for the ICD using only the OCB-128 AEAD cipher and hence she wants to find the data throughput ($R_{sampling}$) of the ICD system, with regards to the harvested energy budget $P_{harvest}$. More specifically, she wants to know for the two (previously mentioned) corner cases, "full sunlight" and "outdoor shadow", how much data the device can sample and securely transmit when we utilize `OCB` AEAD cipher from Table-13.

The per-bit energy consumption of $T_{sampling}$ is

$$E_{sampling} = E_{ADC} + E_{Encryption} + E_{Transmission} \tag{2}$$

First, we quantified the power consumption of the two other parts of the periodic task (except "encryption") as it follows:

- *Heart beat ADC sampling energy (E_{ADC})*: based on the NRF51822 product specification, each 10-bit ADC conversion takes 68ns and draws 260 μA at 1.8 volts[243]. Thus, the energy consumption for a 10-bit ADC sampling is $260\mu \times 68\mu \times 1.8 = 31.824nJ$ (E=I.t.V). Therefore the per-bit energy consumption is approx. 3.2 nJ/bit.

- *Transmission energy ($E_{Transmission}$)*: based on the NRF51822 product specification, with -8dbm signal strength at 2Mbps data-rate, the device will consume nominal energy of 10.5 nJ/bit. We ignore the data transmission packets overheads for simplicity.

Therefore $E_{sampling} = 10.5 + 3.2 + E_{encryption}$.

Obviously the energy used by $T_{sampling}$ during a period of τ should be less than the harvested energy from the solar cells:

$$P_{harvest}.\tau \geq E_{sampling} \times R_{sampling} \times \tau \tag{3}$$

Now we study two corner cases:

- *Full-sunlight*: in this case $9029 \geq (13.7 + E_{sampling}) \times R_{sampling}$.
- *Outdoor shadow*: in this case $947 \geq (13.7 + E_{sampling}) \times R_{sampling}$.

Table 18 presents the maximum obtainable throughput of the ICD based on the harvested energy and the energy consumption of OCB-128 from Table 13. The numbers show the minimum and maximum throughput of the system. For the case that the harvested energy is somewhere between the maximum and minimum, the ICD system can tune the key length or bit-rate in order to achieve the desired performance without running out of energy. A more accurate study of this system needs a research on stochastic behavior of the harvested energy and energy consumption of all periodic and sporadic tasks. Also, the energy consumption of communication can be studied with the presence of error and protocol handshake and overheads. These will be assumed as the future work of this paper.

Table 18. Maximum throughput(bit/sec) of OCB cipher based on the harvested power

	Key lengths		
	128	192	256
Full-Sunlight	220.16	203.44	184.34
Outdoor shadow	23.09	21.33	19.33

7 FURTHER DISCUSSION

During the conducted experiments, we found some considerations regarding the software development techniques that can affect the memory, energy and performance costs. We describe them in this part.

7.1 Bit-Slicing

We have two bit-sliced implementations of `AES`[253] and `PRESENT` [254] in our set. Bit-slicing or byte-slicing is an implementation approach to boost the performance on bit- or byte-oriented algorithms which are intended to run on MCUs with wider (*e.g.* 32-bit) data-paths. A cipher-related example, `AES` is a byte-oriented cipher. Normally for `AES` to run on a 32-bit MCU, 24 bits out of a 32-bit data word stored in a register are empty. The idea is to simply use the three unused bytes of the registers with three other instances of `AES` executions which all run simultaneously. This ideally can quadruplicate performance. This method is called byte-slicing. Usually, the achieved performance is less than 4 times, because the byte-sliced version either requires some extra instructions or some of the instructions cannot be byte-sliced (like modular addition).

Bit-slicing is based on a similar idea but the difference is that each bit of the data word belongs to a different computation. For instance, a 32-bit bit-sliced algorithm computes 32 instances of the same algorithm in parallel and each bit belongs to a different input data. On each instruction, 32 single bits from 32 instances are being computed simultaneously. Bit-slicing is more appropriate for ciphers with bit manipulation structure, like bit permutation.

In general, bit- and byte- slicing prolong the entire algorithm execution time; but computing several instances of the cipher, makes them faster than normal implementation.

Here, we compare two `AES` and `PRESENT` reference codes with their byte-sliced version to see the per-bit performance and energy gain. We can find the bit-sliced results in Table-11 among the other ciphers. Here we focus only on the results *without* a key scheduling phase. For `PRESENT`, bit-slicing has considerable gain. The reason is that the original algorithm contains many bit operations. As only one bit of Arithmatic Logic Unit (ALU) and registers are used on each bit operation, bit-slicing can take advantage of the rest of the unused resources. Therefore, bit-slicing helps to consider `PRESENT` as a low-energy cipher. This is not the case for bit-sliced version of `AES` and the gain is not significant. This is mainly because of the S-Box look-up operation. Table look-up can not be bit-sliced. In other words, reading from different location of the memory is not possible in parallel in common MCUs with a single RAM channel. Therefore, this bit-sliced `AES` implementation

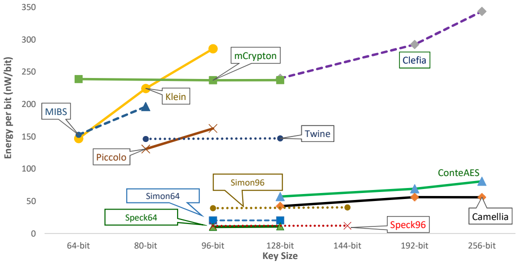


Fig. 5. Effect of the key size on energy consumption

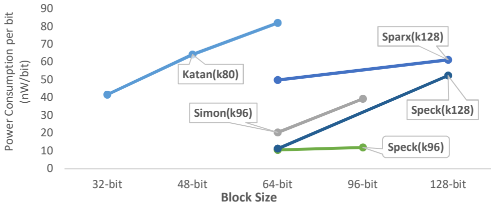


Fig. 6. Effect of the block size on energy consumption

does not use table look-up for S-Box calculation, and instead, calculate bit-sliced S-Box values on-the-fly using its mathematical method[255] which is time consuming.

In conclusion, bit- and byte-slicing can improve the performance and energy consumption, specifically on hardware-oriented ciphers which have several bit operations. This is not the case for the software structures, like look-up tables.

7.2 Manual Optimizations

For some widely-used ciphers (*e.g.* `AES`) there are plenty of implementations available on the Internet. The authors have tried to optimize one criterion of RAM , performance or code size. The optimization normally has an adverse effect on the other criteria. An IoT designer may want to employ one optimization type, according to her desired energy fingerprint. As a case study, we chose three of the well-known and open-source `AES` implementations; namely, TinyAES [5], microAES[6] and Conte's implementation[7] in order to show the effect of manual optimization on software implementation. The results exist in Table 11. Among them, Conte's `AES` has better energy-performance footprints. It has unfolded AES loop iterations to achieve smaller runtime. Moreover, while the other two codes use look-up tables only for S-Box function, Conte's implementation utilizes other look-up tables for the MixColumn function, which makes it faster than the others. Subsequently, Conte's `AES` presents better energy and performance in exchange of memory consumption.

Another example of trading memory for energy and performance is the `PRESENT`results. We chose a 32-bit optimized implementation from [256]. There are two versions of the cipher: one optimized for memory and another for performance. The speed-optimized version uses look-up tables for computation which is faster and memory expensive. As it is expected, speed optimization has drastic improvement on energy and performance.

7.3 Effect of the Key Length

In this part, we inspect the effect of key length on energy consumption. Key length is a security parameter which determines the cipher strength against brute-force attacks. Larger key size means more attacking costs (time or processing) to exhaust the key space by attackers.

Normally, a larger key means more cipher processing time and hence more energy consumption on the device. We examined this effect for ciphers in Table 11 with different key sizes. Figure 5 illustrates this for these ciphers. In the figure, for `Simon` and `Speck` family, the number next to their name is their block size.

Therefore, we examine each cipher with fix block size and different key sizes. For instance, in Figure 5, `SIMON96` is a version of this cipher with 96-bit blocks of data, to which the key size could be 96, 128 and 144 bits. This figure illustrates some ciphers of which their energy consumption significantly increases by the key size; namely, `MIBS`, `KLEIN`, `Clefia`, and `Piccolo`. Two other ciphers, namely, tinyAES and `Camellia` also show slightly alleviated behavior in response to their key size. But, "per-bit" energy consumption of ConteAES, `TWINE`, `mCrypton`, `Simon` and `Speck` are nearly constant for all key sizes. Obviously, these ciphers could be utilized with higher security (larger key size) without significant energy penalty.

7.4 Effect of the Block Size

It is also possible to learn whether larger block sizes yield lower per-bit energy consumption. For this, we again compared ciphers with different block sizes but with the same key length from Table 11. Figure 6 shows these ciphers. The key length is written in parenthesis after each cipher name (*e.g.* Simon(k96)). With this

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[5] https://github.com/kokke/tiny-AES-c [Online; accessed 28-July-2018]

[6] https://github.com/SmarterDM/micro-aes [Online; accessed 28-July-2018]

[7] https://github.com/B-Con/crypto-algorithms [Online; accessed 28-July-2018]

respect, we observe that, in general, smaller block sizes are better choices for low-energy encryption. Another point about `Simon` and `Speck` in Figure 6 is notable: The energy consumption of `Speck` and `SPARX` are almost independent of the block size, which makes it a unique choice based on all design criteria so far.

8 CONCLUSION

This paper identified, evaluated and compared the cryptographic choices of secure communication in an ultra-low-energy IoT device. The study gives the energy consumption (performance and memory consumption) of a large number of crypto algorithms on a real MCU-based IoT device along with the experimental results. The paper also compares the contribution of a few other system-related choices, like transmission bandwidth, signal strength and MCU frequency. The IoT designers can find the obtained results and apply them in the design phase of an energy IoT device. This will reduce the trial and error and the design cost of the device.

9 ACKNOWLEDGMENT

This work is partially carried out under the SERENE-IoT project, a project labeled within the framework of PENTA, the EUREKA cluster for Application and Technology Research in Europe on NanoElectronics.

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