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Survey and Benchmark of Lightweight Block Ciphers for Wireless Sensor Networks*

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Abstract: For security applications in wireless sensor networks (WSNs), choosing best algorithms in terms of energy-efficiency and of small memory requirements is a real challenge because the sensor networks must be autonomous. In (Eisenbarth et al., 2012; Law et al., 2006), the authors have benchmarked on a dedicated platform some block-ciphers and have deduced the best candidates to use in the context of small embedded platforms. This article proposes to study on a dedicated platform of sensors most of the recent lightweight block ciphers as well as some conventional block ciphers. First, we describe the design of the chosen block ciphers with a security summary and we then present some implementation tests performed on our platform.

Introduction

Wireless Sensor Networks (WSNs) are composed of numerous low-cost, low-energy sensor nodes communicating at short distance through wireless links. Sensors are densely deployed to collect and transmit data of the physical world to one or few destinations called the sinks using multi-hop routing protocols. Wireless sensor networks can be really useful in many civil and military areas for collecting, processing and monitoring environmental data. A sensor node contains an integrated sensor, a microprocessor, some memories, a transmitter and an energy battery. Despite the relative simplicity of its basic components, sensor networking offers a great diversity: various hardwares (MicaZ, Telos, SkyMote, AVR or TI micro-controllers), various radio and physical layers (868MHz and 2,4GHz) using different types of modulations, various OS (TinyOS, Contiki, FreeRTOS, JITS), various constraints (real-time, energy, memory or processing), various applications (military or civil uses).

In such a context, a specific care must be invested in the design of the applications, communication protocols, operating systems and of course security protocols that will be used. Lots of protocols have been proposed to enforce the security offered by sensor net-

works. Despite the increasing request in this new area of research, few articles present results of real software implementations or benchmarks concerning the security primitives which can be used in sensor networks. In (Eisenbarth et al., 2012; Law et al., 2006), the authors present such results. In (Law et al., 2006), the authors present benchmark results on a MSP430, a TI 16 bits microcontroller, comparing the most famous block ciphers (including AES, MISTY1, Skipjack,...) and the different possible modes of operations. In (Eisenbarth et al., 2012), the authors present benchmark results on a ATtiny device, a 8 bits microcontroller, of 12 block ciphers, 8 lightweight block ciphers and 4 conventional block ciphers. They also introduce a comparison metric that takes into account both the code size and the cycle count.

This article presents performance results for 17 block ciphers (most of the recent lightweight block ciphers and some conventional block ciphers). This performance results are obtained by testing the dedicated implementations of the algorithm on a MSP430², a TI 16 bits microcontroller which is the corner stone of the nodes WSN430³ used in the deployed Senslab platform⁴ (des Roziers et al., 2011).

This paper is organized as follows: Section 1

²<http://www.ti.com/product/msp430f1611>

³<http://perso.ens-lyon.fr/eric.fleury/Upload/wsn430-docbook/>

⁴<http://www.senslab.info/>

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presents the studied block ciphers. Section 2 presents the dedicated platform and describes the methodology used to perform our benchmarks. Section 3 provides our results and our analysis concerning the benchmarking whereas Section 4 concludes this paper.

1 The studied block ciphers

Our benchmarks concern 17 block ciphers, 12 are lightweight and 5 are conventional block ciphers. Studied block ciphers are listed in Table 1 in alphabetic order.

The main differences between the conventional block ciphers and the lightweight block ciphers are centered on: the block size which is in general 32, 48 or 64 bits for a lightweight block cipher and equal to 64 or 128 bits for a conventional block cipher; the same remark also holds for the different possible key sizes (smaller for lightweight block ciphers); Lightweight block ciphers also rely more on elementary operations (such as binary XOR, binary AND, etc.) leading in an increase of required number of rounds; Lightweight block ciphers generally extremely simplify the key schedule due to memory requirements.

For a complete overview of each implemented block cipher from a design point of view (without describing the key schedule) and from a cryptanalytic point of view (we limit our state of art in the case of unknown key settings and of related key settings, we do not describe attacks in the known or chosen key settings), the reader could refer to (Cazorla et al., 2013).

2 Methodology

In this section, we present the platform used to perform the benchmarks and we also describe the testing framework.

2.1 The dedicated platform

The MSP430 is a Texas Instrument microcontroller running with an external 8MHz clock. This microcontroller is programmable via a JTAG connection. It integrates a 48 KBytes flash memory, a 10 Koctets RAM memory, 48 configurable Inputs/Outputs, 12-bit analog-to-digital conversion pins, a watchdog, 2 serial communication ports and 2 configurable timers. This microcontroller is compatible with most of real-time operating systems such as FreeRTOS.

All the codes were written in C. We used the GCC toolchain for MSP430 family to flash programs into the microcontroller. This includes the GNU C compiler (GCC), the assembler and linker (binutils), the debugger (GDB), and some other tools needed to make a complete development environment for the MSP430. These tools can be used on Windows, Linux, BSD and most other flavors of Unix. We used msp430-gcc version 4.6.3.

2.2 Methodology

We measured the performance of the algorithms as well as the memory consumption. To obtain the performance, we used simulator coming with mspdebug. This simulator is able to give the number of clock cycles spent at any point of the program execution. Although it is only a simulator, it is cycle-accurate and the experiments we made on real hardware confirmed the results obtained.

Concerning the memory consumption, we distinguish between the need of read-only memory (ROM) and writable memory (RAM). The ROM is used to store the code as well as tables that do not need to be modified – for instance, the F-table of skipjack. We obtain the size of the ROM needed simply by declaring as *static const* the concerned variables and getting the size of the text section in the *elf* file. In order to get the size of RAM needed, mspdebug tells us until which address the execution stack was modified.

3 Results

3.1 CPU cycles and energy consumption

Table 2 gives the performance of the algorithms.

3.2 Memory requirements

Table 2 reports the memory consumption of the algorithms. It shows the requirements of read-only memory (code + read-only tables) as well as the amount of RAM needed to store the stack and modifiable data. We can see that the requirement of RAM is very similar and very small, except for the CLEFIA and the KATAN families. The memory requirements of these functions is due to the use of large tables in the key scheduling phase.

On the contrary, the need of read-only memory is very different from one algorithm to an other. Whereas TEA and XTEA requires only 1354 and 1394 bytes of ROM to execute, KTANTAN requires

| NAME (<i>Nb/Nk</i>) | Reference | Struct. | Nb rounds |
|---------------------------------|-----------------------------|------------|------------|
| AES-128* (128/128) | (FIPS 197, 2001) | SPN | 10 |
| CLEFIA-128* (128/128) | (Shirai et al., 2007) | Feistel | 18 |
| DESXL (64/184) | (Leander et al., 2007) | Feistel | 16 |
| HIGHT (64/128) | (Hong et al., 2006) | Feistel | 32 |
| IDEA* (64/128) | (Lai and Massey, 1990) | Lai-Massey | 8.5 |
| KATAN & KTANTAN (32, 48, 64/80) | (Cannière et al., 2009) | Stream | 254 |
| KLEIN (64/64, 80 and 96) | (Gong et al., 2011) | SPN | 12, 16, 20 |
| LBLOCK (64/80) | (Wu and Zhang, 2011) | Feistel | 32 |
| LED (64/64 and 128) | (Guo et al., 2011) | SPN | 32/48 |
| mCrypton (64/64, 96 and 128) | (Lim and Korkishko, 2005) | SPN | 12 |
| MIBS (64/64 and 80) | (Izadi et al., 2009) | Feistel | 32 |
| Noekeon* (128/128) | (Daemen et al., 2000) | SPN | 16 |
| Piccolo (64/80 and 128) | (Shibutani et al., 2011) | Feistel | 25/31 |
| PRESENT (64/80 and 128) | (Bogdanov et al., 2007) | SPN | 31 |
| TEA & XTEA (64/128) | (Wheeler and Needham, 1994) | Feistel | 64 |
| TWINE (64/ 80 and 128) | (Suzaki et al., 2012) | Feistel | 36 |
| SEA (96/96,...) | (Standaert et al., 2006) | Feistel | Var. |
| SKIPJACK* (64/80) | (NIST, 1998) | Feistel | 32 |

Table 1: Studied block ciphers. *Nb* means the size of the input/output block in bits; *Nk* means the size of the key in bits. * designates the conventional block ciphers in opposite to lightweight block ciphers.

16252 bytes in its 64-bits version. The ROM consumption of the KATAN family is due to the tables used to store the bitfields (see Section 1).

3.3 Analysis

We consider 6 different metrics here: cycle count for enc.+key and for dec.+key, cycles/bytes for enc.+key and for dec.+key, code size (in bytes), RAM use (in bytes) and the metric introduced in (Eisenbarth et al., 2012) that is code size \times cycle count product, normalized by the block size (see Fig. 1). We detail in this Section some particular observations.

First, due to sensor memory requirement, we consider compact implementations. As shown in Table 3, TEA and XTEA have memory size less than 1500 bytes whereas NOEKEON, LED mCrypton, Piccolo, SEA and TWINE have memory footprint between 2000 and 3000 bytes which is really reasonable. At the contrary, all the KATAN and KTANTAN version have huge memory footprints due to their particular design which has the same cost when enciphering/deciphering 32, 48 or 64 blocks in parallel. In terms of RAM occupancy, HIGHT, LBlock, mCrypton, MIBS, Skipjack, TEA and XTEA require less than 20 bytes of RAM which is really performing.

Concerning performance, TEA, XTEA and the AES are the only ones that require less than 2000 cycles/byte. Some lightweight designs have poor performance: KATAN, KTANTAN, LED, mCrypton and PRESENT whereas the others (DESXL, NOEKEON,

HIGHT, KLEIN, LBlock, Piccolo, TWINE) use less than 5500 cycles/bytes. IDEA is efficient in encryption but as expected and due to the key schedule inefficient in decryption.

Lastly, the combined metric in Figure 1 first shows the excellent size vs. performance trade-off offered by the AES. Among the low-cost ciphers, NOEKEON, TEA and XTEA have also an excellent behavior. In the same way, HIGHT, Piccolo and TWINE provide good trade-offs whereas KATAN and KTANTAN are not present in the Figure due to their too bad behaviors.

4 Conclusion

We have presented here some benchmarks performed on lightweight block ciphers, the traditional ones and the new ones on a dedicated platform which is a sensor. In total, 17 ciphers have been implemented and analyzed keeping in mind that the compactness is an important issue in the sensor world. They show that some well-suited block ciphers such as Piccolo, TWINE, XTEA or the AES have good performance considering the trade-off between code size and cycle count. We also see that most of the ciphers specially dedicated to hardware (such as LED, PRESENT or KATAN and KTANTAN) have poor results.

| Algorithm | Block Size (bits) | Enc.+key: cycle count | Enc.+key : cycles/byte | Dec.+key: cycle Count | Dec.+key: cycles/byte |
|---------------|-------------------|-----------------------|------------------------|-----------------------|-----------------------|
| AES | 128 | 30257 | 1891 | 38508 | 2406 |
| CLEFIA128 | 128 | 98145 | 6134 | 101855 | 6365 |
| CLEFIA192 | 128 | 150314 | 9394 | 123333 | 7708 |
| CLEFIA256 | 128 | 155658 | 9728 | 145291 | 9080 |
| DESXL | 64 | 26055 | 3256 | 66913 | 8364 |
| DIRnoekeon | 128 | 26291 | 1643 | 27129 | 1695 |
| HIGHT | 64 | 32372 | 4046 | 32623 | 4077 |
| IDEA | 64 | 31402 | 3925 | 163380 | 20422 |
| INDnoekeon | 128 | 52564 | 3285 | 53435 | 3339 |
| KATAN32 | 32 | 744279 | 186069 | 717056 | 179264 |
| KATAN48 | 48 | 1127271 | 187878 | 1053680 | 175613 |
| KATAN64 | 64 | 1518391 | 189798 | 1397924 | 174740 |
| KLEIN64 | 64 | 29514 | 3689 | 100600 | 12575 |
| KLEIN80 | 64 | 40278 | 5034 | 135369 | 16921 |
| KLEIN96 | 64 | 51502 | 6437 | 170789 | 21348 |
| KTANTAN32 | 32 | 10233211 | 2558302 | 10193489 | 2548372 |
| KTANTAN48 | 48 | 10614933 | 1769155 | 10525067 | 1754177 |
| KTANTAN64 | 64 | 11004783 | 1375597 | 10864265 | 1358033 |
| LBlock | 64 | 42954 | 5369 | 22005 | 2750 |
| LED128 | 64 | 1341488 | 167686 | 1345152 | 168144 |
| LED128.tcalc | 64 | 268721 | 33590 | 274953 | 34369 |
| LED128.tdur | 64 | 171056 | 21382 | 173832 | 21729 |
| LED64 | 64 | 894680 | 111835 | 897352 | 112169 |
| LED64.tcalc | 64 | 212409 | 26551 | 217401 | 27175 |
| LED64.tdur | 64 | 114872 | 14359 | 116280 | 14535 |
| MCRYPTON64 | 64 | 107803 | 13475 | 219870 | 27483 |
| MCRYPTON96 | 64 | 108499 | 13562 | 220320 | 27540 |
| MCRYPTON128 | 64 | 108415 | 13551 | 220568 | 27571 |
| MIBS64 | 64 | 49056 | 6132 | 52890 | 6611 |
| MIBS80 | 64 | 58688 | 7336 | 39842 | 4980 |
| PRESENT_SIZE | 64 | 491602 | 61450 | 489813 | 61226 |
| PRESENT_SPEED | 64 | 364587 | 45573 | 368731 | 46091 |
| Piccolo128 | 64 | 36497 | 4562 | 39600 | 4950 |
| Piccolo80 | 64 | 32106 | 4013 | 34630 | 4328 |
| SEA | 96 | 119455 | 9954 | 120158 | 10013 |
| SKIPJACK | 64 | 84923 | 10615 | 123368 | 15421 |
| TEA | 64 | 8785 | 1098 | 9129 | 1141 |
| TWINE | 128 | 82003 | 5125 | 60932 | 3808 |
| XTEA | 64 | 9287 | 1160 | 9631 | 1203 |

Table 2: Software performance.

| Function | RAM | ROM | Function | RAM | ROM | Function | RAM | ROM |
|--------------|------|-------|---------------|------|-------|--------------|------|-------|
| AES | 19 | 4460 | CLEFIA128 | 180 | 4780 | CLEFIA192 | 268 | 5010 |
| CLEFIA256 | 268 | 4924 | DESXL | 112 | 16816 | DIRnoekeon | 34 | 2710 |
| HIGHT | 18 | 3130 | IDEA | 82 | 3140 | INDnoekeon | 34 | 2784 |
| KATAN32 | 1881 | 5816 | KATAN48 | 1969 | 7076 | KATAN64 | 1953 | 8348 |
| KLEIN64 | 36 | 5486 | KLEIN80 | 38 | 5676 | KLEIN96 | 39 | 5862 |
| KTANTAN32 | 614 | 10516 | KTANTAN48 | 702 | 11764 | KTANTAN64 | 790 | 16252 |
| LBlock | 13 | 3568 | LED128 | 41 | 2648 | LED128.tcalc | 41 | 2948 |
| LED128.tdur | 41 | 2264 | LED64 | 41 | 2670 | LED64.tcalc | 41 | 2498 |
| LED64.tdur | 41 | 2264 | MCRYPTON64 | 18 | 2726 | MCRYPTON96 | 20 | 2834 |
| MCRYPTON128 | 24 | 3108 | MIBS64 | 29 | 3184 | MIBS80 | 16 | 3138 |
| PRESENT_SIZE | 142 | 4964 | PRESENT_SPEED | 142 | 4814 | Piccolo128 | 91 | 2510 |
| Piccolo80 | 79 | 2434 | SEA | 24 | 2804 | SKIPJACK | 19 | 6628 |
| TEA | 13 | 1354 | TWINE | 23 | 2216 | XTEA | 11 | 1394 |

Table 3: Memory usage. The column RAM means RAM requirement in bytes whereas the column ROM means Size of read-only data in bytes.

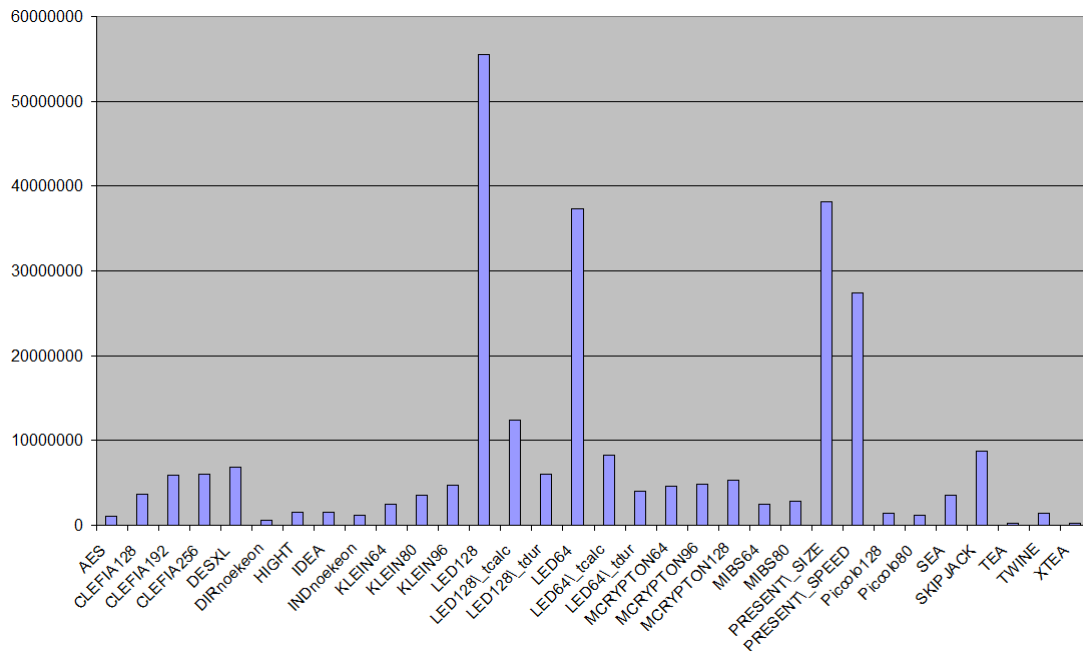


Figure 1: Metric introduced in (Eisenbarth et al., 2012): code size × cycle count product/block size.

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