BitCracker: BitLocker meets GPUs

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Abstract

BitLocker is a full-disk encryption feature available in recent Windows versions. It is designed to protect data by providing encryption for entire volumes and it makes use of a number of different authentication methods. In this paper we present a solution, named BitCracker, to attempt the decryption, by means of a dictionary attack, of memory units encrypted by BitLocker with a user supplied password or the recovery password. To that purpose, we resort to GPU (Graphics Processing Units) that are, by now, widely used as general-purpose coprocessors in high performance computing applications. BitLocker decryption process requires the computation of a very large number of SHA-256 hashes and also AES, so we propose a very fast solution, highly tuned for Nvidia GPU, for both of them. We analyze the performance of our CUDA implementation on several Nvidia GPUs and we carry out a comparison of our SHA-256 hash with the Hashcat password cracker tool. Finally, we present our OpenCL version, recently released as a plugin of the John The Ripper tool.

Keywords: BitLocker, hash, SHA-256, AES, GPU, CUDA, cryptographic attack, password cracking

1. Introduction

BitLocker is a data protection feature that integrates with the Windows operating system and addresses the threats of data theft or exposure from lost, stolen, or inappropriately decommissioned computers. It offers a number of different authentication methods, like Trusted Platform Module, Smart Key, Recovery Password, user supplied password. BitLocker features a pretty complex proprietary architecture but it also leverages some well-known algorithms, like SHA-256 and AES. It is possible, and relatively easy (to the purpose, commercial tools are available [12]) to instantly decrypt disks and volumes protected with BitLocker by using the decryption key extracted from the main memory (RAM). In addition, it is also possible to decrypt for offline analysis or instantly mount BitLocker volumes by utilizing the escrow key (BitLocker Recovery Key) extracted from a users Microsoft Account or retrieved from Active Directory.

If the decryption key can not be retrieved, the only alternative remains to unlock password-protected disks by attacking the password. The same, above mentioned, commercial tools offer this as an option but in a quite generic form (*i.e.*, without taking into account the specific features of BitLocker). Moreover, according to some comments¹, they may be also not fully reliable. The goal of the present paper is to describe our approach to attack BitLocker passwordprotected storage units. We carefully studied available information about Bit-Locker architecture and directly inspected several types of units in order to find out how to minimize the amount of work required to check a candidate password. The platforms we use for the attack are based on Nvidia GPUs and we carefully optimized the most computing intensive parts of the procedure achieving a performance that is, at least, comparable with that provided by well-know password crackers like Hashcat [7] for the evaluation of the SHA-256 digest function. However the main goal of our work is not providing an alternative to Hashcat as a general framework for dictionary attacks but to offer the first open-source high performance tool to test the security of storage units protected by BitLocker using the user password and recovery password authentication methods. The rest of the paper is organized as follows: Section 2 describes BitLocker and in particular the decryption procedure of the so-called Volume Master Key: Section 3 describes our attack, that we name BitCracker, to BitLocker focusing on the optimizations made to improve the performance of the execution of the SHA-256 algorithm (that is the computational bottleneck of the decryption procedure); Section 4 presents the performance (as number of passwords that is possible to check *per* second) of BitCracker using different variants of the CUDA² architecture showing that there is an improvement of more than a factor 8 moving from the Kepler to the Volta architecture. Sec-

 $^{^{1}\}rm https://blog.elcomsoft.com/2016/07/breaking-bitlocker-encryption-brute-forcing-the-backdoor-part-ii/$

²https://developer.nvidia.com/cuda-zone

tion 5 presents our OpenCL 3 implementation comparing the password rate with results in Section 4. Section 6 reports a comparison of the performance, limited to the evaluation of the SHA-256 digest, of BitCracker with respect to Hashcat. Finally Section 7 summarizes the results and provides indications for future activities.

2. BitLocker

BitLocker (formerly BitLocker Drive Encryption) is a full-disk encryption feature included in the Ultimate and Enterprise editions of Windows Vista and Windows 7, the Pro and Enterprise editions of Windows 8 and Windows 8.1, Windows Server 2008 and Windows 10. It is designed to protect data by providing encryption for entire volumes.

BitLocker can encrypt several types of memory units like internal hard disks or external memory devices ⁴(flash memories, external hard disks, etc..) offering a number of different authentication methods, like Trusted Platform Module, Smart Key, Recovery Key, password, etc.. In this paper we focus on two different authentication modes: the *user password mode*, in which the user, to encrypt or decrypt a memory device, must type a password (as represented in Figure 1) and the *recovery password mode*, that is a 48-digit key generated by BitLocker (regardless of the authentication method chosen by the user) when encrypting a memory device⁵. By means of the recovery password the user can access an encrypted device in the event that she/he can't unlock the device normally.

During the encryption procedure, each sector in the volume is encrypted individually, with a part of the encryption key being derived from the sector number itself. This means that two sectors containing identical unencrypted data will result in different encrypted bytes being written to the disk, making it much harder to attempt to discover keys by creating and encrypting known data. BitLocker uses a complex hierarchy of keys to encrypt devices. The sectors themselves are encrypted by using a key called the Full-Volume Encryption Key (FVEK). The FVEK is not used by or accessible to users and it is, in turn, encrypted with a key called the Volume Master Key (VMK). This level of abstraction gives some unique benefits, but it makes the process a bit more difficult to understand. The FVEK is kept as a closely guarded secret because, if it were compromised, all of the sectors would need to be reencrypted. Since that would be a time-consuming operation, it is much better to avoid it. Instead, the system works with the VMK. The FVEK (encrypted with the VMK) is stored on the disk itself, as part of the volume metadata and it is never written to disk unencrypted. The VMK is also encrypted with

³https://www.khronos.org/opencl

⁴BitLocker To Go feature

 $^{^5 \}rm Microsoft$ Blog: Recover Password method: https://docs.microsoft.com/enus/windows/device-security/bitlocker/bitlocker-recovery-guide-plan

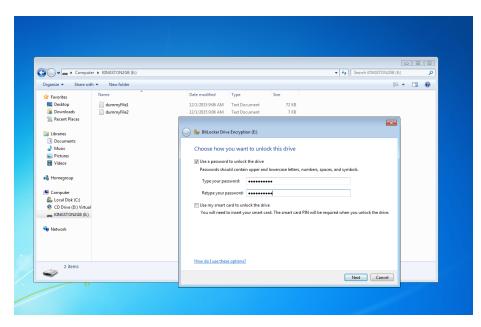


Figure 1: BitLocker encryption of an USB pendrive using the password authentication method.

one or more (combination of) authentication mechanisms as above mentioned; for instance, if the memory device has been encrypted with the user password method, in the volume metadata there are two encrypted VMKs: the VMK_U, that is the VMK encrypted with the user password, and the VMK_R, that is the VMK encrypted with the recovery password. Both FVEK and VMK are encrypted according to the Counter with CBM-MAC (CCM) mode of AES.

During the decryption procedure (Figure 2) BitLocker, depending on the authentication method in use, starts to decrypt the VMK. Then, if it obtains the right value for the VMK, it decrypts in turn the FVEK and then the entire memory device.

The attack described in the present paper aims at decrypting the correct VMK key which belongs to an encrypted memory unit through a dictionary attack to the user password or to the recovery password. That is, if an attacker is able to find the password to correctly decrypt the VMK key, she/he is able to decrypt the entire memory unit with that password.

2.1. User Password VMK Decryption Procedure

To gain an insight about the workings of our attack, more information are necessary about the VMK decryption procedure (Figure 3) when the authentication method is a user password (see also [4] [6] and [5]):

- 1. the user provides the password;
- 2. SHA-256 is executed twice on it;

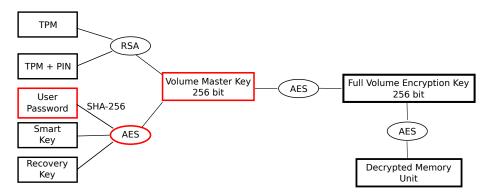


Figure 2: BitLocker encryption/decryption scheme

3. there is a loop of 0x100000 iterations, in which SHA-256 is applied to a structure like:

typedef struct {
<pre>unsigned char updateHash[32]; //last SHA-256 hash calculated</pre>
<pre>unsigned char passwordHash[32]; //hash from step 2</pre>
unsigned char salt[16];
<pre>uint64_t hash_count; // number of hash in loop, incremented</pre>
<pre>// at the end of every iteration</pre>
<pre>} bitlockerMessage;</pre>

- 4. this loop produces an intermediate key, used with AES to encrypt the Initialization Vector (IV) (derived from a *nonce*);
- 5. XOR between encrypted IV and encrypted Message Authentication Code (MAC) to obtain the decrypted MAC;
- 6. XOR between encrypted IV and encrypted VMK to obtain the decrypted VMK;
- 7. if the MAC, calculated on the decrypted VMK, is equal to the decrypted MAC, the input password and the decrypted VMK are correct;

All the elements required by the decryption procedure (like VMK, MAC, IV, etc..) can be found inside the encrypted volume. In fact during the encryption, BitLocker stores not only encrypted data but also metadata that provide information about encryption type, keys position, OS version, file system version and so on. Thanks to [5], [6], [4] and [2] we understood how to get all of those information reading the BitLocker Drive Encryption (BDE) encrypted format.

After an initial header, every BDE volume contains 3 (for backup purposes) FVE (Full Volume Encryption) metadata blocks, each one composed by a block header, a metadata header and an array of metadata entries.

In Figure 4 we report an example of FVE block belonging to a memory unit encrypted with Windows 8.1, enumerating the most interesting parts:

- 1. The "-FVE-FS-" signature, which marks the beginning of an FVE block
- 2. The Windows version number

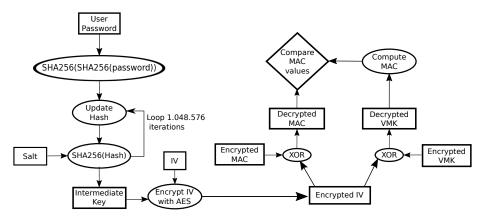


Figure 3: VMK decryption procedure

- 3. The type and value of a VMK metadata entry
- 4. According to this value, the VMK has been encrypted using the user password authentication method
- 5. The salt of the VMK
- 6. According to this value, the type of VMK encryption is AES-CCM
- 7. Nonce
- 8. Message Authentication Code
- 9. Finally, the VMK

Our attack executes the BitLocker decryption procedure with several performance improvements:

- The code has been optimized for NVIDIA GPUs (using the CUDA environment) (Section 3)
- We introduced a preprocessing step, before starting the main attack, to store in memory useful information for the SHA-256 based main loop (Section 3.3)
- We found a way to remove the final MAC computation and comparison (Section 3.4).

2.2. Recovery Password VMK Decryption Procedure

As above mentioned, the recovery password is a kind of passe-partout for all the authentication methods. According to [2], the recovery password is a 48digit number composed by eight groups of six digits; each group of six digits must be divisible by eleven and must be less than 720896. Finally, the sixth digit in each group is a checksum digit. For instance, a valid recovery password is:

 $236808 \hbox{-} 089419 \hbox{-} 192665 \hbox{-} 495704 \hbox{-} 618299 \hbox{-} 073414 \hbox{-} 538373 \hbox{-} 542366$

0	20FFFA0	FB56F4F4	DEF58AD4	1FE9DDFF	AAE41FCE	E7F91AA4	F06FA477	4F41AC27	6F57E3AA
9	20FFFC0	79B810	A45B7D1A	BE8DC360	5641C955	7BF9CFA2	3C2BB5D0	315BF1C6	1D9C9058
2	20FFFE0	79ADA0DB	9922C0E6	695F57C3	4FD4F01F	72464F22	BF6D68D6	CE3BBE81	3A9FF1CC
5	2100000	2D465645	2D46532D	34000200	04000400	00005005	00000000	00000000	B6270000
9	2100020	00001002	00000000	00562503	00000000	00AC3A04	00000000	00041102	00000000
1	2100040	FC020000	01000000	30000000	FC020000	E8F49E1E	29591946	A1D5EA44	8F0F8DE8
9	2100060	09000000	02800000	850A46C9	C6A1CF01	38000700	02000100	4D004100	43005200
3	2100080	4F005300	2D005000	402000	46003A00	20003100	37002F00	30003700	2F003200
١	21000A0	30003100	34000000	E0000200	08000100	C16D3F96	1106AA.4	B48802E2	289CBB5F
1	21000C0	FØ1BE2D7	C6A1CF01	00000020	60000000	03000100	01100000	ØA8B9DØ6	55D3900E
5	21000E0	9F67280A	DC27B5D7	50000000	05000100	B0599AD6	C6A1CF01	02000000	BCBAEB2A
9	2100100	A3A0694	E95965B9	8CD1218F	01549F55	BABE2FAB	3B108DAB	238-0B42	B556B474
3	2100120	19AA82B2	A0D702EB	459371-18	A0B438D6	AEB02FE7	55B4D415	50000000	05000100
9	2100140	B0599AD6	C6A1CF01	03000000	C16658F5	4140B3D9	ØBE6DE9E	03B1FE90	033A2C7D
3	2100160	F7127BCD	16CB013C	F778C120	72142C48	4C9C291A	496FC0EB	D8C21C33	B595A9C1
9	2100180	587ACFC6	D8BB9663	20010200	08000100	ØB16A27B	B2DBAB41	BD206165	68B479E7

Figure 4: FVE metadata block, BitLocker Windows 8.1

The number of all possible recovery password candidates is huge, thus building the entire dictionary would require too much storage.

The algorithm used by BitLocker to encrypt a device using the recovery password is similar to the user password one with few differences during the initial SHA-256 application.

Figure 5 extends the Figure 4; in the same FVE block (initial signature at mark number 1) there are 2 encrypted VMKs: the first one (VMK_U) is encrypted with the user password (mark number 2) and the second one (VMK_R) with the recovery password (mark number 3). The hardest part of the recovery password attack is to find the VMK_R in the FVE blocks: each authentication method (i.e. TPM, TPM+PIN, user password, smart card, etc..) has its own FVE block format and each one stores the VMK_R into a different index. Currently, we are able to find VMK_R in case of devices encrypted with user password and smart card while TPM and TPM+PIN methods obfuscate the interesting part of the FVE block. BitCracker performance in case of recovery password attack is similar to the performance in case of user password; for this reason, during the rest of this paper, we report only about the performance of user password attacks.

3. BitCracker

Our software, named *BitCracker*, aims at finding (starting from a dictionary) the key of a memory unit encrypted using the password authentication method of BitLocker. To achieve that goal, BitCracker uses GPUs (*Graphics Processing Units* 6) to execute the algorithm described in Section 3.5 according

⁶https://it.wikipedia.org/wiki/Graphics_Processing_Unit

20FFFA0	FB56F4F4	DEF58AD4	1FE9DDFF	AAE41FCE	E7F91AA4	F06FA477	4F41AC27	6F57E3AA
20FFFC0	C579B810	A45B7D1A	BE8DC360	5641C955	7BF9CFA2	3C2BB5D0	315BF1C6	1D9C9058
20FFFE0	79ADA0DB	9922C0E6	695F57C3	4FD4F01F	72464F22	BF6D68D6	CE3BBE81	3A9FF1CC
2100000	2D465645	2D46532D	34000200	04000400	00005005	00000000	00000000	B6270000
2100020	00001002	00000000	00562503	00000000	00AC3A04	00000000	00041102	00000000
2100040	FC020000	01000000	30000000	FC020000	E8F49E1E	29591946	A1D5EA44	8F0F8DE8
2100060	09000000	02800000	850A46C9	C6A1CF01	38000700	02000100	4D004100	43005200
2100080	4F005300	2D005000	43002000	46003A00	20003100	37002F00	30003700	2F003200
21000A0	30003100	34000000	E0000200	08000100	C16D3F96	1106AA44	B48802E2	289CBB5F
21000C0	F01BE2D7	C6A1CF01	00000020	6000000	03000100	01100000	0A8B9D06	55D3900E
21000E0	9F67280A	DC27B5D7	50000000	05000100	B0599AD6	C6A1CF01	02000000	BCBAEB2A
2100100	CF3A0694	E95965B9	8CD1218F	01549F55	BABE2FAB	3B108DAB	238F0B42	B556B474
2100120	19AA82B2	A0D702EB	45937F18	A0B438D6	AEB02FE7	55B4D415	50000000	05000100
2100140	B0599AD6	C6A1CF01	03000000	C16658F5	4140B3D9	ØBE6DE9E	03B1FE90	033A2C7D
2100160	F7127BCD	16CB013C	F778C120	72142C48	4C9C291A	496FC0EB	D8C21C33	B595A9C1
2100180	587ACFC6	D8BB9663	20010200	08000100	0B16A27B	B2DBAB41	BD206165	68B479E7
21001A0	ØØDBFEDC	C6A1CF01	0000008	AC000000	03000100	00100000	CDA1B7E0	308CFFE3
21001C0	D4E3EC9A	FC7A3E61	40001200	05000100	B0599AD6	C6A1CF01	04000000	507CF880
21001E0	8A5EDD14	3F032625	BE64735A	6E8EFD19	E9D9F98F	DBE48709	607C4445	A70DB465
2100200	02268F60	7C1F58BB	50001300	05000100	B0599AD6	C6A1CF01	05000000	D7FA779A
2100220	8D14E2AF	83066012	2E7245C0	A4C013DB	63878577	661E4E17	8BE99836	C45F588B
2100240	13700588	32041DF8	F62D85E0	B26E81B7	8C677B69	A033E501	50000000	05000100
2100260	B0599AD6	C6A1CF01	06000000	58516D80	CB347B7A	992E9EB0	5F8157D7	9AC2F66D
2100280	101C796C	E6EC40C9	1706E4D9	289BCD7B	27901627	95A8FDC6	0696846D	7FCA26F0
21002A0	F75288FE	07536706	40000300	05000100	B0599AD6	C6A1CF01	07000000	ABEB2B23
21002C0	95883A25	BA525A5E	6404BE6E	7076BD88	8E1003D7	BD68E2C0	39B58853	370E1878

Figure 5: FVE metadata block, BitLocker Windows 8.1, two Volume Master Keys

to the Single Program, Multiple Data (SPMD) paradigm: all threads execute same instructions on different test passwords. In this Section we describe more in details the behaviour of our algorithm and several optimizations we introduced to enhance its performance.

3.1. SHA-256

As described in section 2.1, SHA-256 is widely used in the BitLocker decryption scheme to obtain the intermediate key from the user password, so we focused our work in the improvement of its performance on GPU. Algorithm 1 presents a brief pseudo-algorithm of SHA-256 standard (for a full description, see [3]) that is necessary for a better understanding of the work we did. It is apparent that:

- first 16 words of W depends on the original message;
- there are two loops, the first to compute the M^N message blocks and the second one to compute the 64 rounds of SHA-256;
- circular shift is widely used and aritmetic operations are only bitwise, sum, and subtraction.

Algorithm 1 SHA-256 standard algorithm

- 1: Define $Ch(x,y,z) = (x \land y) \oplus (\neg x \land z)$
- 2: Define Maj(x,y,z) = $(x \land y) \oplus (x \land z) \oplus (y \land z)$
- 3: Define $ROTR^n(\mathbf{x}) = (x >> n) \lor (x << w-n)$ with $0 \leq n < w, w = 32$
- 4: Define $SHR^n(\mathbf{x}) = (x >> n)$
- 5: Define $\sigma_0^{256} = ROTR^7(x) \oplus ROTR^{18}(x) \oplus SHR^3(x)$ 6: Define $\sigma_1^{256} = ROTR^{17}(x) \oplus ROTR^{19}(x) \oplus SHR^{10}(x)$
- 7: Define M_t^i as the t-th 32-bit word belonging to the i-th 512-bit block of the padded message
- 8: Define K[64] as an array of constants

9:

- 10: for i = 1 to N do
- Prepare the message schedule W_t 11:

$$W_t = \begin{cases} M_t^i & \text{if } 0 \le t \le 15\\ \sigma_1^{256}(W_{t-2}) + W_{t-7} + \sigma_0^{256}(W_{t-15}) + W_{t-16} & \text{if } 16 \le t \le 63 \end{cases}$$

Initialize the 8 working variables: a,b,c,d,e,f,g,h with the $(i-1)^{st}$ hash value: 12:

$$\begin{split} a &= H_0^{i-1}; b = H_1^{i-1}; c = H_2^{i-1}; d = H_3^{i-1}; \\ e &= H_4^{i-1}; f = H_5^{i-1}; g = H_6^{i-1}; h = H_7^{i-1} \end{split}$$

- for t = 0 to 63 do 13:
- $T_{1} = h + [ROTR^{6}(e) \oplus ROTR^{11}(e) \oplus ROTR^{25}(e)] + Ch(e, f, g) + K_{t}^{256} + W_{t}$ 14:
- $T_{2} = [ROTR^{2}(a) \oplus ROTR^{13}(a) \oplus ROTR^{22}(a)] + Maj(a, b, c)$ 15:
- 16:h=g; g=f; f=e;
- $e=d + T_1$ 17:
- d=c; c=b; b=a;18:
- $a = T_1 + T_2$ 19:
- end for 20:
- Compute the i^{th} intermediate hash value H^i 21:

$$\begin{split} H_0^i &= a + H_0^{i-1}; H_1^i = b + H_1^{i-1}; \\ H_2^i &= c + H_2^{i-1}; H_3^i = d + H_3^{i-1}; \\ H_4^i &= e + H_4^{i-1}; H_5^i = f + H_5^{i-1}; \\ H_6^i &= g + H_6^{i-1}; H_7^i = h + H_7^{i-1}; \end{split}$$

22: end for

3.2. CUDA optimizations

Our first implementation of the SHA-256 algorithm, was a plain C implementation quite similar to the algorithm described in Section 3.1:

Listing 1: SHA-256 C implementation

```
for(i=0; i<64; i++){
    T1 = h + S1(e) + CH(e,f,g) + K[i] + W[i];
    T2 = S0(a) + MAJ(a,b,c);
    h = g; g = f;
    f = e; e = d + T1;
    d = c; c = b;
    b = a; a = T1 + T2;
}</pre>
```

There are many assignments and loops with no GPU optimization. We ran our first test on a NVIDIA GPU Tesla K80 for an initial performance evaluation, reaching up to 80 passwords per second.

After that, inspired by Nayuki implementation ⁷, we wrote a code without loops (only inline instructions), a lower number of operations, high throughput arithmetic instructions (see Section 4), removing all the useless aritmethics like index calculation (w - n) or assignments (d=c; c=b; ...).

All GPU threads follow the same execution flow in a single SHA-256 execution: no shared memory is used and each thread works on its subset of passwords stored in global memory; variables used during execution are stored (as much as possible) in GPU registers and all operations are performed inline, *i.e.*, there are no loops (except for the loop of 0x100000 SHA-256) and very few arrays index computations to limit *local* memory usage (more later). The type of instructions used are: 32-bit integer add, 32-bit integer shift, 32-bit bitwise AND, OR, XOR (see Section 4 for further details).

Listing 2: Final version of SHA-256

 $^{^7{\}rm SHA-256}$ Nayuki implementation: http://nayuki.eigenstate.org/page/fast-sha2-hashes-in-x86-assembly (Checked on May 20 2018)

We reserve special attention to the usage of GPU *local* memory, because it can dramatically decrease performance. Usually, if there is an array inside a kernel code declared as a local variable but accessed dynamically inside the code (*i.e.*, array indexing is calculated at runtime) CUDA stores that array in local memory (instead of using registers) and this penalizes the performance since the *local* memory is actually a part of the (slow) *global* memory of the GPU. We reduced *local* memory usage as much as possible (we double-checked it by looking at the low-level PTX code) by replacing index calculations and loops.

During a second round of tests using the same NVIDIA GPU Tesla K80, we reached up to 103 passwords per second.

After that, we focused on the VMK decryption algorithm (Figure 3): in Section 3.3 we describe our enhancement during the second SHA-256 in each iteration of the main loop while in Section 3.4 we explain how the final comparison of the MAC can be easily removed.

3.3. First improvement: W Words

The most time-consuming part of the decryption algorithm is the loop of 0x100000 (1.048.576) SHA-256 operations, since a single hash involves many arithmetic operations. Moreover, during each iteration, the SHA-256 algorithm is applied twice to the 128 byte structure *bitlockerMessage* (Section 2.1) which is composed by several fields as shown in Table 1.

64-byte	block #1		64-byte block	< #2	
32 bytes	32 bytes	16 bytes	8 bytes	32 bytes	8 bytes
updated_hash	password_hash	salt	hash_count	padding	message size
		fixed for each	between 0 and		
variable	fixed	encrypted unit	0x100000	fixed	fixed to 88

Table 1: BitLocker SHA-256 message

As mentioned above, the first 16 W words depend on the original message and the others on the first 16 words. Therefore, looking at the message in Figure 1 we were able to compute all possible W words useful for the SHA-256 of the second block of the message at each iteration in the loop, with no need to repeat many arithmetic operations during each iteration. Indeed, since for each encrypted memory unit, salt, padding and message size are always the same and hash_count is a number between 0 and (0x100000-1), we can precompute all the W words, that are:

$1.048.576 * 64 = 67.108.864 \ words * 4 \ byte \simeq 256Mb$

This kind of improvement is specific for BitLocker (precomputation can be done if there is a part of the input message that is known ahead of time) and cannot be applied to a general SHA-256 implementation.

In the beginning, we stored pre-computed W words in global memory, but we found that texture memory (due to the texture caching capabilities) could improve timings (see Section 4). For the first block, we can not precompute anything, because *updateHash* changes at every iteration.

Thanks to this improvement we reduced the CUDA registers pressure and usage, being able to use 64 registers for each CUDA thread and then 1024 threads for each CUDA block (about 100% occupancy). We measure a performance enhancement, reaching up to 340 passwords per second.

3.4. Second improvement: MAC comparison

During our analysis of the decrypted VMK's structure, using different Windows versions (7, 8.1 and 10) and a number of encrypted devices, we noticed several interesting facts:

1. The size of the VMK is always 44 bytes

- 2. First 12 bytes of decrypted VMK (Table 2) hold information about the key
 - First 2 bytes are the size of VMK, that is always 44 (0x002c)
 - Bytes 4 and 5 are the *version* number, always equal to 1
 - Byte 8 and 9 are the type of encryption. In case of user password, BitLocker always uses AES-CCM with a 256 bit key. So, according to the Microsoft standard, this value is between 0x2000 and 0x2005
- 3. Remaining 32 bytes are the key

Byte	0	1	2	3	4	5	6	7	8	9	10	11
Value	2c	00	00	00	01	00	00	00	03	20	00	00

Table 2: Example of initial 12 bytes of VMK decryption key

Following those considerations, we removed the MAC test doing a simple check on the initial 12 bytes of the decrypted VMK, as shown in Figure 6.

On our GPU Tesla K80 performance reached 385 passwords per second (see Section 4 for further details).

To check the reliability of our solution, we tested BitCracker with several storage devices (both internal and USB-connected hard disks) encrypted by using passwords having between 8 and 16 characters under Windows 7 Enterprise Edition, Windows 7 Ultimate Edition and Windows 8 Pro N and Windows 10 Enterprise Edition (testing both BitLocker's compatible and non compatible modes) ⁸.

Although BitCracker always returned the correct output, some false positive may occur with this improved VMK check; for this reason BitCracker can be executed in 2 different modes: with (slower solution) or without (faster solution) the MAC comparison .

⁸Recently Microsoft introduced the BitLocker "Not Compatible" encryption mode in Windows 10: sectors of the memory device are encrypted with XTS-AES instead of AES-CCM. This change doesn't affect BitCracker algorithm because there isn't any difference in the decryption procedure of the VMK.

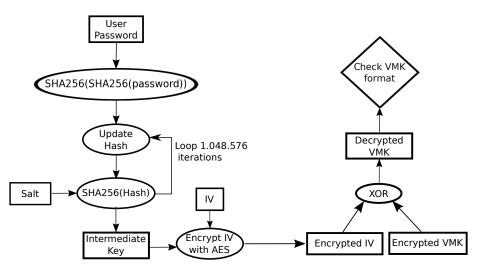


Figure 6: VMK decryption procedure improved

3.5. Final Architecture

We implemented the final solution, shown in Algorithm 2, using CUDA and OpenCL doing an extensive performance analysis in Sections 4 and 5.

As described in Section 2.1, the main SHA-256 loop produces the intermediate key, that must be used as an AES key to encrypt the IV in order to decrypt the VMK. We have implemented our own AES version customized for GPU environment [11], used in line 15 of Algorithm 2. In Figure 7 we represent the entire BitCracker's general procedure outside of the GPU kernels.

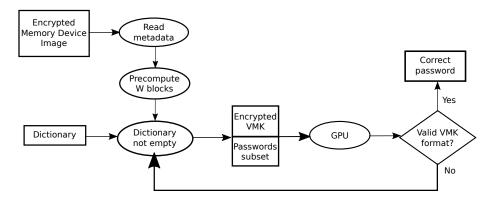


Figure 7: BitCracker general algorithm

Algorithm 2 BitCracker Kernel

1:	function BitCrackerKernel(password, WTextureWords, IV, VMK)
2:	hash = Sha256SingleExec(Sha256SingleExec(password));
3:	for $i = 1$ to 0x100000 do
4:	SetStartValue(a,b,c,d,e,f,g,h);
5:	\triangleright /* SHA-256 on the first message block */
6:	Compute first 32 W words, depending on $hash_{i-i}$
7:	Exec first 32 rounds
8:	Compute second 32 W words
9:	Exec second 32 rounds
10:	Update $hash_i$ value
11:	\triangleright /* SHA-256 on the second message block */
12:	Exec 64 rounds, reading W blocks from WTextureWords
13:	Update $hash_i$ value
14:	end for
15:	Crypt IV with final hash value as key of AES
16:	VMKDecrypted = XOR(IVCrypted, VMK)
17:	if checkVMK(VMKDecrypted) then
18:	return true;
19:	end if
20:	end function

4. CUDA implementation performance

In this Section we present the results of benchmarking activities of our stand-alone CUDA implementation of BitCracker with the improvements described in previous sections. We used several NVIDIA GPUs whose features are summarized in Table 3 9 .

Acronim	Name	Arch	CC	# SM	SM Clock	CUDA
GFT	GeForce Titan	Kepler	3.5	14	836 MHz	7.0
GTK80	Tesla K80	Kepler	3.5	13	$875 \mathrm{MHz}$	7.0/7.5
GFTX	GeForce Titan X	Maxwell	5.2	24	1001 MHz	7.5
GTP100	Tesla P100	Pascal	6.1	56	1189 MHz	8.0
GTV100	Tesla V100	Volta	7.0	80	$1290 \mathrm{~MHz}$	9.0

Table 3: NVIDIA GPUs used for bench

During the following tests we always set the number of CUDA blocks to the maximum number of SM allowed by the GPU architecture: further increasing this number does not improve performance. The number of CUDA threads per block is always 1024 because each thread requires no more than 64 registers (we reached the maximum occupancy).

 $^{^9\,}CC$ is Compute Capability while SM is Stream Multiprocessors

4.1. Kepler Architecture

We started to benchmark our final improved solution on the *Kepler* architecture using GPUs GTK80 (Table 4) and GFT (Table 5).

Blocks	Threads/Block	Pwds/Thread	Pwds/Kernel	Seconds	Pwds/Sec
1	1.024	1	1.024	30	33
1	1.024	8	8.192	245	33
2	1.024	8	16.384	247	66
4	1.024	8	32.768	248	132
8	1.024	8	65.536	253	258
13	1.024	8	106.496	276	385

Table 4: GTK80 benchmarks

Blocks	Threads/Block	Pwds/Thread	Pwds/Kernel	Seconds	Pwds/Sec
1	1.024	1	1.024	39	25
1	1.024	8	8.192	318	25
14	1.024	8	114.688	364	314

Table 5: GFT benchmarks

The more the input grows, the better BitCracker performs. Increasing the number of blocks, each one with the same number of passwords per thread (*i.e.*, 8), leads to a better performance since the kernel launching overhead (that is basically constant) is distributed among more blocks.

The GTK80 appears to be faster with respect to the GTF. For instance, in the 8 passwords per thread last test-case the GTK80 is able to check ~ 70 more passwords per second than the GFT even if it has one less multiprocessor. To shed some light on this difference, we report in Table 6 a summary of instructions types and occurrences in one out of 0x100000 iterations of the SHA-256 loop.

Instruction	Throughput GTK80	Throughput GTF	# Occurrence
32-bit integer add	160	160	1.121
32-bit integer shift	64	32	2.016
32-bit bitwise	160	160	1.600

Table 6: Instructions throughput

As described in the NVIDIA developer zone 10 :

- to maximize instruction throughput, the application should minimize the use of arithmetic instructions with low throughput;
- throughput is given in number of operations per clock cycle per multiprocessor. For a warp size of 32, one instruction corresponds to 32 opera-

¹⁰NVIDIA Developer Zone: https://technet.microsoft.com/en-us/library/cc162804.aspx

tions, so if N is the number of operations per clock cycle, the instruction throughput is N/32 instructions per clock cycle.

Since the 32-bit integer shift is the most used instruction (due to the circular shift, see Section 3) the fact that its throughput in the GTK80 is twice than in the GFT could explain the significant difference in performance. Due to the relevance of the shift instruction, the circular shift is translated inside the PTX code in a *funnel shift* operation (faster than *regular shift*) even if this is not explicitly specified in the CUDA code. That is, an instruction like:

$$((x) << 26) \mid ((x) >> 6))$$

becomes, in PTX code:

shf.l.wrap.b32 %r8165, %r8152, %r8152, 26

We limit the number of registers for a single thread to 64. This choice makes it possible to have 1.024 threads for each block since each Stream Multiprocessor for Kepler and Maxwell GPU has 65536 32-bit registers. On the GTK80 there is no memory spilling while on the GFT we have just 24 bytes of memory spilling (handled by the L1 cache). Nevertheless, this configuration offers the best performance. The occupancy level is close to 100% provided that there are enough passwords in input (shared memory is not a limiting factor since we do not use it).

In Table 7 we report some of the metrics provided by the CUDA profiler **nvprof** running a synthetic test in which the number of loop iterations is limited to 65.536 to prevent the overflow of some counters that occurred in the full 0x100000 iterations execution:

Instructions issued	8.072.134.346
Instruction replay overhead	0,000003
Global memory load	2.208
Global memory store trans.	1
Local memory load trans.	0
Local memory store trans.	0
Arithmetic Function Unit Utilization	High(9)
Texture cache hit rate	99.80%

Table 7: nvprof Metrics on GTK80

The number of *instructions issued* is greater than the number of *global memory transactions*, so BitCracker can be considered, somehow, instructions limited (this is not surprising since there are very few global memory load/store operations). The metrics about the texture cache confirms that the use of texture memory for W words (instead of global memory) is optimal. There is no instruction serialization inside a single warp (usually serialization is due to memory conflicts) because *instruction replay overhead* metrics is very close to 0. Finally, there are no local memory transactions due to our optimization

work described in Section 3.2.

4.2. Maxwell Architecture

In Table 8 we present the same benchmarks of the previous Section executed on the GFTX, using CC3.5 and CC5.2 (both available on the GPU).

CC	Blocks	Threads/Block	Pwds/Thread	Pwds/Kernel	Seconds	Pwds/Sec
3.5	1	1.024	1	1.024	24	42
3.5	1	1.024	8	8.192	191	42
3.5	24	1.024	8	196.608	212	925
3.5	24	1.024	128	3.145.728	3496	900
5.2	1	1.024	1	1.024	23	44
5.2	1	1.024	8	8.192	188	43
5.2	24	1.024	8	196.608	210	933
5.2	24	1.024	128	3.145.728	3369	933

Table 8: GFTX benchmarks, CC3.5 and CC5.2

It is worth to note that performance improves both due to the higher number of multiprocessors available in the new generation of NVIDIA cards and for the enhancements in integer instructions throughput ¹¹. This confirms that a well-tuned CUDA code can benefit from new features with a very limited effort.

With CUDA 7.5 NVIDIA released new PTX instructions like IADD3 and LOP3, that support a range of 3-operand logic operations, such as (A&B&C), $(A\&B\&\neg C)$, $(A\&B \lor C)$ and so on. According to the release notes in ¹², those instructions are fully supported on GPUs with CC 5.0 or greater, while on a Kepler architecture they are simulated; therefore we optimized BitCracker code for Maxwell cards.

In other words, the LOP3 instruction combines three operands according to a Truth Table expressed as a hexadecimal number; in Table 9 there is an example of a XOR Truth Table. See ¹³ for further details and examples.

 $^{^{11}\}mathrm{NVIDIA}$ Developer Zone Maxwell: https://developer.nvidia.com/maxwell-compute-architecture

 $^{^{12} \}rm NVIDIA\ Devblog:\ https://devblogs.nvidia.com/parallelforall/new-features-cuda-7-5$

 $^{^{13}\}rm NVIDIA$ PTX LOP3: http://docs.nvidia.com/cuda/parallel-thread-execution/# logic-and-shift-instructions-lop3

a	b	с	result
0	0	0	0
0	0	1	1
0	1	0	1
0	1	1	0
1	0	0	1
1	0	1	0
1	1	0	0
1	1	1	1
			0x96

Table 9: XOR Truth Table

Looking at Table 8, Maxwell card performance increases when using 5.2 compute capability with an intensive use of the above mentioned PTX instructions for all the bitwise boolean operations involved in the SHA-256 algorithm described in 3.2.

4.3. Pascal architecture

In Table 10, we summarize our benchmarks on GTP100. The performance improvement is close to a \times 2 factor with respect to the Maxwell architecture even if the main advantage of the new architecture (*i.e.*, the memory bandwidth that is about three times higher with respect to the *Kepler* architecture) has limited impact on a compute-intensive application like BitCracker.

CC	Blocks	Threads/Block	Pwds/Thread	Pwds/Kernel	Seconds	Pwds/Sec
6.1	1	1.024	1	1.024	38	26
6.1	56	1.024	1	57.344	40	1.418
6.1	56	1.024	8	458.752	336	1.363
6.1	56	1.024	128	7.340.032	5444	1.348

Table 10: GTP100 benchmark

4.4. Volta architecture

In Table 11, we summarize our benchmarks on GTV100. The performance improvement is more than $\times 2$ factor with respect to the Pascal architecture.

CC	Blocks	Threads/Block	Pwds/Thread	Pwds/Kernel	Seconds	Pwds/Sec
7.0	1	1.024	1	1.024	24	41
7.0	80	1.024	1	81.920	25	3.252
7.0	80	1.024	8	655.360	210	3.107

Table 11: GTV100 benchmark

5. **OpenCL** Implementation

In order to make BitCracker available also to non-NVIDIA GPUs, we developed an OpenCL implementation.

In Table 12 we report performance of BitCracker-OpenCL standalone version tested with an AMD Radeon HD 7990 Malta¹⁴, using OpenCL version 1.2 (1800.5), confirming that BitCracker OpenCL is able to run on non-NVIDIA GPUs.

Work Groups	Local Work Group size	Pwds/Thread	Pwds/Kernel	Seconds	Pwds/Sec
32	256	1	8.192	41	197
64	256	1	16.384	68	241
32	256	64	524.288	2657	197
64	256	32	524.288	2175	241
64	256	48	786.432	3263	241

Table 12: Benchmarks OpenCL version, AMD Radeon HD 7990 Malta

The results, reported in Table 13, show that the OpenCL implementation is just 5% slower with respect to the CUDA original implementation on the same platform (see Table 8).

Work Groups	Threads/Block	Pwds/Thread	Pwds/Kernel	Seconds	Pwds/Sec
1	1.024	1	1.024	23	44
24	1.024	8	196.608	220	893
24	1.024	128	3.145.728	3555	884

Table 13: GFTX, OpenCL 1.2

6. Performance comparison

It is possible to evaluate BitCracker's performance by looking at the number of hashes per second that it computes (we recall that the check of each password requires 2.097.154 hashes, as described in Section 2.1). The number of hashes *per* second that BitCracker is able to perform is summarized in Table 14^{15} .

GPU	Password/Sec	Hash/Sec
GFT	303	635 MH/s
GTK80	385	$807 \ \mathrm{MH/s}$
GFTX	933	1.957 MH/s
GTP100	1.418	$2.973 \ \mathrm{MH/s}$
GTV100	3.252	$6.820 \ \mathrm{MH/s}$

Table 14: BitCracker's hashes per second, CUDA implementation

6.1. Hashcat comparison

To assess BitCracker performance, we carried out a comparison with the SHA-256 format (-m 1400) Hashcat [7] v4.1.0. We highlight that this is not a completely fair comparison since Hashcat does not execute exactly the same

¹⁴by courtesy of the Openwall HPC Village[13].

 $^{^{15}\}mathrm{MH}$ stands for MegaHashs

BitCracker's algorithm (BitCracker performs other operations beyond SHA-256) and it currently supports OpenCL only. The test aims at providing an idea about the number of SHA256 that each one of them is able to compute *per* second. We ran a test on the GTV100 using the following parameters:

- -m 1400 : Raw SHA-256 hash format
- -a 3 : Mask attack
- ?a?a?a?a?a?a?a?a?a : Mask to specify passwords of 8 characters
- -d : specify the GTV100 device
- -O and -w 3 as suggested by Hashcat itself to improve performance

The resulting number of hashes per second is 7590 MH/s that is comparable to BitCracker's best performance on the same GPU.

6.2. John The Ripper

In order to take advantage of their system of *rules* for wordlist generation, our OpenCL implementation has been released as a John the Ripper (Jumbo version) [8] plugin (format name *bitlocker-opencl*); the source code can be found here [9] whereas the wiki reference page is here [10]. When running *bitlocker-opencl* format, the John The Ripper internal engine auto-tunes all the OpenCL parameters (like local and global work groups). Running a simple test like:

./john -format=bitlocker-opencl -wordlist=wordlist.txt hashFile.txt

we reached up to 3150 passwords/second on the GTV100.

The John The Ripper team developed a CPU format of our attack which can be invoked using flag "*-format=bitlocker*". We reached up to 78 password-s/second on a CPU Intel(R) Xeon(R) v4, 2.20GHz.

6.3. Performance overview

In Figure 8 we plot the best performance (passwords *per* second) obtained testing different GPUs and software frameworks (green bars refer to the CUDA implementation whereas blue bars refer to the OpenCL implementation).

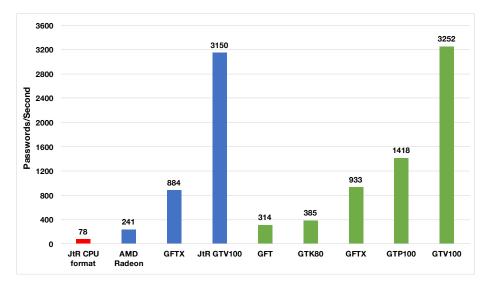


Figure 8: BitCracker implementations comparison

7. Conclusions

We presented the first open-source implementation of a tool for efficient dictionary attacks to the BitLocker crypto system.

The results show that our BitCracker may compete with a state-of-the art password cracker in terms of raw performance on the basic computational kernels whilst it is the only one providing specific shortcuts to speedup the BitLocker decryption procedure. We can conclude that, although the complex architecture of BitLocker reduces significatly the number of passwords that is possible to test in a unit of time, with respect to other crypto-systems (e.g., OpenPGP), it is still necessary to pay special attention in the choice of the user password since, with a single high-end GPU, more than a quarter-billion of passwords can be tested in a day (~ 3000 passwords per second on a GTV100 × 86400 seconds $\simeq 260$ million in a day). Our implementations of SHA-256, fully customized for the CUDA-C environment, can be reused (provided that the W words optimization is turned off, since it cannot be applied to a general situation) for any procedure that requires to use that hash function (e.g., HMAC-SHA256).

Other possible improvements include the enhancement of BitCracker by adding a mask mode attack and/or a smart reading of the input dictionary (e.g. by assigning a probability to them) that are available in most widely used password crackers.

We released our CUDA and OpenCL standalone implementations on GitHub here [14]. In order to take advantage of their system of *rules* for wordlist generation, our OpenCL implementation has been released also as a John the Ripper (Jumbo version) [8] format. We're also planning to release BitCracker within Hashcat.

8. Acknowledgment

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