Firmware Insider: Bluetooth Randomness is Mostly Random

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Abstract

Bluetooth chips must include a Random Number Generator (RNG). This RNG is used internally within cryptographic primitives but also exposed to the operating system for chip-external applications. In general, it is a black box with security-critical authentication and encryption mechanisms depending on it. In this paper, we evaluate the quality of RNGs in various Broadcom and Cypress Bluetooth chips. We find that the RNG implementation significantly changed over the last decade. Moreover, most devices implement an insecure Pseudo-Random Number Generator (PRNG) fallback. Multiple popular devices, such as the Samsung Galaxy S8 and its variants as well as an iPhone, rely on the weak fallback due to missing a Hardware Random Number Generator (HRNG). We statistically evaluate the output of various HRNGs in chips used by hundreds of millions of devices. While the Broadcom and Cypress HRNGs pass advanced tests, it remains indistinguishable for users if a Bluetooth chip implements a secure RNG without an extensive analysis as in this paper. We describe our measurement methods and publish our tools to enable further public testing.

1 Introduction

High-quality random numbers ensure security within cryptographic methods. The Bluetooth 5.2 specification makes no exception to this—it requires a Bluetooth chip to provide at least a PRNG compliant to FIPS PUB 140-2 [7, 14, p. 953]. Various security-relevant functions depend on random numbers, such as generating authentication and encryption keys, nonces within Secure Simple Pairing (SSP), or passkeys used in authentication. Moreover, embedded and Internet of Things (IoT) devices with Bluetooth Low Energy (BLE) can request random numbers locally from the chip [7, p. 2521]. Thus, a Bluetooth chip’s RNG quality can also be relevant to external applications.

According to the specification, the RNG shall be tested against FIPS SP800-22 [4]. Recommended test suites are Diehard, Dieharder, and the NIST tools [8, 15]. We choose the Dieharder suite, as it implements the most extensive tests. Verification of the randomness properties is not straightforward. Even though these test suites exist, the local Host Controller Interface (HCI) that enables the operating system to request random numbers from the chip introduces a lot of overhead per request and only returns an 8 B number. In contrast, the Dieharder test suite requires at least 1 GB of unique data to return meaningful results, making randomness tests a challenge.

Statistical tests might not uncover all issues within an RNG. The underlying implementation can be a HRNG or PRNG. The latter is part of the chip’s firmware and could have flaws only detectable by reverse-engineering the implementation. While the HRNG could also have flaws that stay undetected by statistical tests, this goes beyond the analysis of this paper. The according datasheets, which are only available for a few of the older chips, do not cover any details about the HRNG.

In this paper, we reverse-engineer and measure the RNG implementations of Broadcom and Cypress Bluetooth chips. In particular, we analyze the RNGs on 20 chips, including those on the most recent iPhones and Samsung Galaxy S series. To this end, we root or jailbreak those devices, dump their firmware with the InternalBlue framework [13], and reverse-engineer these. Moreover, we write custom patches that increase the RNG output to make measurements with the Dieharder test suite feasible. These patches need to be customized for each chip and the according operating systems, which are Android, Linux, iOS, and macOS. Our main findings are as follows:

- All chips (except the Samsung Galaxy S8 variants and an iPhone) contain a HRNG. Yet, most implement a PRNG fallback in case the HRNG is not available.
- The PRNG is based on various predictable inputs, which significantly reduces its entropy. We show that an active

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1 Cypress acquired parts of Broadcom in 2016 [11], and the code bases diverged since then.
over-the-air attacker can infer and manipulate PRNG values.

- Multiple patches were applied to the RNG implementation over time, such as adding a cache. The PRNG fallback is no longer present in the most recent Broadcom chips but Cypress still maintains this code.

- An HRNG is missing on the European version of the Samsung Galaxy S8 and its variants in the S8+ and Note 8, which was sold approximately 40 million times.

- After responsibly disclosing the issue, the firmware was patched in May 2020 in Samsung’s Android release as well as in iOS 13.5 for an unspecified iPhone.

Flaws in the RNG allow attacks on Bluetooth authentication and encryption mechanisms. Recently, attacks on the Elliptic-curve Diffie–Hellman (ECDH) key exchange and key negotiation showed how sensitive these mechanisms are [1, 2, 5, 17]. While these flaws were in the specification itself, RNG issues are implementation-specific and rather opaque.

We initiated responsible disclosure with Broadcom, Cypress, and a selection of their customers on January 12, 2020. The weak PRNG implementation was assigned CVE-2020-6616. Broadcom denied that the PRNG fallback was used on any of their devices despite it being present in their firmware—until we found and reported that the HRNG code and register mappings were missing on the Samsung Galaxy S8 on February 1, 2020.

This paper is structured as follows: In Section 2, we provide background information on how the RNG is used within security-critical parts of the Bluetooth specification. We reverse-engineer 20 firmware variants in Section 3 and continue with HRNG and PRNG measurements as well as PRNG attacks in Section 4. We discuss further aspects in Section 5. We conclude our findings in Section 6.

2 RNG Usage Within Bluetooth

A predictable or known RNG has a severe impact on security-relevant functions in Bluetooth. The Bluetooth 5.2 specification only vaguely mentions that this is the case [7, p. 953], but does not provide any context which functions break if the RNG does not meet the requirements. Thus, we outline concrete examples where the RNG matters. These examples are not a complete list—this would exceed the scope of this paper. In general, random numbers are used in many more places within the Bluetooth specification, and an unknown number of applications within host applications.

2.1 Active MITM Attack on Pairing with Numeric Comparison

During the initial pairing of two Bluetooth devices, the protocol requires user input to prevent an active Machine-in-the-Middle (MITM) attack, as no previous key material exists on any of the devices to identify the other one. Bluetooth SSP provides different methods for this kind of authentication, a commonly used one is Numeric Comparison [7, p. 985]: Both devices display a 6-digit number to the user and the user checks whether both numbers are equal. While Numeric Comparison was introduced for Classic Bluetooth with SSP, it is also supported by BLE under the name LE Secure Connections since Bluetooth 4.2 [7, p. 269], because the previous LE Legacy Pairing is broken by design [16].

Numeric Comparison happens in the second stage of authentication, after both parties have exchanged their ECDH public keys. Device B, the non-initiating party, starts by generating a random number Nb and sending a commitment Cb of Nb and both public keys to device A. Device A answers by generating a random number, Na, as well, which it sends to B. Finally, B sends Nb to A. A checks whether Cb is indeed a commitment of Nb and both parties hash Na, Nb and both public keys to a 6-digit number, which is then displayed on both devices.

If there was an active MITM attacker, the public keys that are fed into the hash function would differ and the two devices would display different values with high probability. However, this depends on the attacker not being able to change either Na or Nb to search for a second pre-image of the hash function, as the 6-digit output does not protect against brute-force attacks. Therefore, the protocol is designed in a way that no party can decide on their random number after seeing the random number of the other party—A by sending its number first and B by committing to its randomness before seeing Na.

The security of the Numeric Comparison protocol crucially relies on the hiding property of the commitment, i.e., that no party can calculate Nb from the commitment Cb. As the commitment is deterministic, this requires Nb to be a number with high entropy. Now, if an attacker can predict Nb or small set of possible Nbs, they can check for Nb by calculating the commitment again and comparing it to Cb. If successful, they can use their knowledge of Nb to create a value Na’, sent to B, such that both devices display the same 6-digit code even though the public keys fed into the hash function differ. For the full attack, see Figure 1.

2.2 LE Randomness Within Android

BLE uses the Security Manager Protocol (SMP) for pairing in LE Secure Connections and LE Legacy Pairing [7, p. 1666]. SMP resides on top of Bluetooth Low Energy (LE) data Protocol Data Units (PDUs) and initiates secure keys. Encryption is then started and stopped with LE link control PDUs inde-
Figure 1: Numeric Comparison protocol attack vector [7, p. 986].

When initiating a BLE pairing on Android 6–10, the HCI command `LE_Rand` is called multiple times. This way, Android receives specification-compliant random numbers within its Bluetooth stack, but keeps control over the keys itself. We further investigate the current Android master branch as of April 2020 [3]. All randomness-related function calls originate from the file `smp_keys.cc`.

During a BLE pairing in Just Works mode, the functions `smp_create_private_key` and `smp_start_nonce_generation` are called. These use random inputs from the Bluetooth chip’s RNG. `smp_create_private_key` directly fills the ECDH private key by calling the Bluetooth RNG via HCI four times in a row and then calculates a public key based on this. Thus, an attacker who knows the internal RNG state can infer the ECDH private key.

After creating the ECDH key pair, the value generated with `smp_start_nonce_generation` is sent in plaintext over-the-air and also contains RNG data. Then, an LE link control PDU `LL_ENC_REQ` is sent [7, p. 2898], which also contains values from the Bluetooth RNG, but is generated locally on the chip without Android interaction.

This means that on Android, directly after using the Bluetooth RNG for creating a private key, further RNG values that could leak the internal RNG state are sent in plaintext over-the-air. Note that this behavior is not required by the Bluetooth specification, e.g., iOS 13 does not call the Bluetooth RNG upon SMP key generation.

3 Firmware Variant Analysis

In the following, we compare the RNG function across 20 firmware versions of even more devices. Sales numbers are rather vague and older devices might no longer be in use, but in total, the chips we analyzed are used in hundreds of millions if not even in a billion of devices. An overview of these is shown in Table 1. Since the firmware is located in the ROM and built during device development, the firmware build date is at least a year before the device release date. For some MacBooks and the Raspberry Pi 4, it is even five years. Moreover, some build dates do not represent the exact state of the libraries that were compiled into it. Thus, the table is sorted by firmware variants.

We obtain firmware dumps and locate the RNG function as described in Section 3.1. Based on this analysis, we identify five variants (see Section 3.2). We provide a pseudo-code description of the main variants in Section 3.3.

3.1 Firmware Symbols and Comparison Methods

`InternalBlue` enables firmware ROM and RAM dumps on various operating systems to extract the firmware from Broadcom and Cypress chips [13]. The extraction requires physical device access and rooting or jailbreaking of mobile devices. Moreover, such firmware dumps do not contain any symbols or strings. Thus, reverse-engineering the RNG is not straightforward.
Table 1: RNG implementation variants in 20 Broadcom and Cypress chips.

| Variant | Chip       | Device                        | Build Date  | HRNG Location | PRNG | Cache                  |
|---------|------------|-------------------------------|-------------|---------------|------|------------------------|
| 1       | BCM2046A2  | iMac Late 2009                | 2007        | 0xE9A00, 3 regs | Minimal (inline) | No                      |
|         | BCM2070B0  | MacBook 2011                  | Jul 9 2008  | 0xE9A00, 3 regs | Minimal (inline) | No                      |
|         | BCM2070A1  | Asus USB Dongle, Thinkpad T420| Feb (?) 2010| 0xEA204, 3 regs | Minimal (inline) | No                      |
| 2       | BCM4335C0  | Google Nexus 5                | Dec 11 2012 | 0x314004, 3 regs | Advanced (inline) | No                      |
|         | BCM4345B0  | iPhone 6                      | Jul 15 2013 | 0x314004, 3 regs | Advanced (inline) | No                      |
|         | BCM43430A1 | MacBook Pro early 2015        | Dec 23 2013 | 0x314004, 3 regs | Advanced (inline) | No                      |
|         | BCM4345C0  | Raspberry Pi 3/Zero W         | Jun 2 2014  | 0x352600, 3 regs | Advanced (inline) | No                      |
|         | BCM4358A3  | Samsung Galaxy S6, Nexus 6P   | Oct 23 2014 | 0x314004, 3 regs | Advanced (inline) | No                      |
|         | BCM4345C1  | iPhone SE                     | Jan 27 2015 | 0x314004, 3 regs | Advanced (inline) | No                      |
|         | BCM4364B0  | MacBook/iMac 2017–2019       | Aug 21 2015 | 0x352600, 3 regs | Advanced (inline) | No                      |
|         | BCM4355C0  | iPhone 7                      | Sep 14 2015 | 0x352600, 3 regs | Advanced (inline) | No                      |
|         | BCM20703A2 | MacBook/iMac 2016–2017       | Oct 22 2015 | 0x314004, 3 regs | Advanced (inline) | No                      |
|         | CYW20719B1 | Evaluation board             | Jan 17 2017 | 0x352600, 3 regs | Advanced, 8 regs | Yes, breaks after 32 elements |
| 3       | CYW20735B1 | Evaluation board             | Jan 18 2018 | 0x352600, 3 regs | Advanced, 5 regs | Yes, with minor fixes |
|         | CYW20719B1 | Evaluation board             | May 22 2018 | 0x352600, 3 regs | Advanced, 8 regs | Yes, breaks after 32 elements |
| 4       | BCM4347B0  | Samsung Galaxy S8/S8+/Note 8 | Jun 3 2016  | Not mapped    | Only option | No                      |
| 5       | BCM4347B1  | iPhone 8/8/XR                 | Oct 11 2016 | 0x352600, 4 regs | None | Asynchronous 32x cache |
|         | BCM4375B1  | Samsung Galaxy S10/20        | Apr 13 2018 | 0x352600, 4 regs | None | Asynchronous 32x cache |
|         | BCM4378B1  | iPhone 11/SE2                | Oct 25 2018 | 0x602600, 4 regs | None | Asynchronous 32x cache |

The Cypress evaluation kits allow to develop an IoT application with WICED Studio [10]. This application is running on the same ARM core as the Bluetooth firmware. Thus, WICED Studio includes a file called patch.elf to link the application during the build process. This patch file contains global function and variable names. Furthermore, each board’s *map*.h file contains hardware register names. WICED Studio also includes symbols in an Advanced RISC Machine (ARM) compiler specific format for the Broadcom BCM20703A2 Wi-Fi/Bluetooth combo chip in the files ram_ext.symdefs and 20703mapa0.h.

We use these partial symbols for static firmware analysis of the RNG, which is internally provided by the function rbg_rand. Since the HRNG is only mapped to two different locations throughout all variants, we can locate these in further firmware variants. The oldest variant is mapped to previously unknown addresses, but uses the same magic value 0x200FFFFF when accessing the HRNG.

### Implementation Details

#### 3.2 Identified Variants

Table 1 compares the implementations of the function rbg_rand. Regardless of the implementation variant, rbg_rand always returns a 4 B random number. Overall, we identify five different variants within firmware released over more than a decade.

1. **Minimal PRNG Fallback** The oldest variant contains the worst PRNG fallback. If no HRNG is available, it skips waiting for a new random number and performs a static calculation based on the current time—which might lead to zero entropy.

2. **Advanced PRNG Fallback** This variant is similar to variant (1) but the PRNG implementation is more advanced and does not only consider time.

3. **Cache and Advanced PRNG Fallback** Cypress introduced a cache that is constantly filled with 32 4 B random numbers, probably to increase performance. Within this variant, also the registers used by the PRNG vary and some that tend to be static were removed.

4. **Advanced PRNG Only** This variant is similar to variant (2) but has the PRNG as only option. The HRNG access is missing within the firmware and dynamic analysis reveals that it is not mapped at all.

5. **Asynchronous Cache and No PRNG** The newest variant is a complete rewrite of the rbg library by Broadcom. The cache is filled asynchronously in the background, the HRNG has an additional register, and the PRNG fallback was removed.

#### 3.3 Implementation Details

Variant (2), the Advanced PRNG Fallback, is the most common variant that we found. Since we have partial symbols for this variant, we can reconstruct the original logic of the HRNG access (Listing 1) and PRNG implementation (Listing 2). Note that except from the complete rewrite in variant (5), the code throughout all variants is very similar.

The HRNG is accessed with the three mapped registers rbg_control, rbg_status, and rbg_random_num. A new
random number is requested by writing 1 to \texttt{rbg\_control}. The \texttt{rbg\_status} indicates if the HRNG is available in general and if it currently has a fresh random number. The random number itself is accessible via \texttt{rbg\_random\_num}. If the HRNG is available in general, the \texttt{rbg\_rand} function enters an endless loop until a new random value is available. As this loop might take longer, it pets the watchdog.

The PRNG depends on two timing values, which are the Bluetooth clock \texttt{dc\_ nbtc\_clk} and system clock \texttt{timer1\_value}. The 4 B Bluetooth clock is comparably slow, runs in steps of 312.5 \textmu s \,[7, p. 415], and is shared over-the-air. In comparison, the system clock passes faster and is not directly known. Depending on the platform, it is either 2 B or 4 B. The remaining PRNG values are acquired from signal reception characteristics. If the PRNG was not used before, it is initialized based on the current memory contents. Otherwise, the last value within the PRNG store is taken. Since the \texttt{rbg\_rand} function only returns 4 B, the entropy of these values is combined by calculating a Cyclic Redundancy Check (CRC).

The older variant (1), the \textit{Minimal PRNG Fallback}, is even worse. The fallback only performs a static calculation based on the current time, as shown in Listing 3. The 4 B time register is increased by one every 0.005 s.

### 4 HRNG and PRNG Tests

The function \texttt{rbg\_rand} can be analyzed statically based on firmware dumps, however, it must also be validated on physical hardware. For example, the code accessing the HRNG was missing in the firmware of the \textit{Samsung Galaxy S8}. However, the code might be present and the test if the HRNG register is available could still return \texttt{false}. Furthermore, if the PRNG is accessed in absence of the HRNG, the entropy of the registers that it is accessing becomes relevant. In the following, we first measure the HRNG in Section 4.1 and then measure the PRNG fallback for the devices using it in Section 4.2. Additionally, we discuss specification-compliant attacks to change PRNG inputs and infer the current PRNG state over-the-air in Section 4.3.

#### 4.1 HRNG Measurements

The only existing interface to acquire random numbers of the Bluetooth chip is the Host Controller Interface (HCI) command \texttt{LE\_Rand} \,[7, p. 2521]. After successful execution, this command is answered with an HCI event containing an 8 B random number. In theory, this could already be used on any off-the-shelf device to measure the RNG quality. However, the only existing interface to acquire random numbers of the Bluetooth chip is the Host Controller Interface (HCI) command \texttt{LE\_Rand} \,[7, p. 2521]. After successful execution, this command is answered with an HCI event containing an 8 B random number. In theory, this could already be used on any off-the-shelf device to measure the RNG quality. However, the older variant (1), the \textit{Minimal PRNG Fallback}, is even worse. The fallback only performs a static calculation based on the current time, as shown in Listing 3. The 4 B time register is increased by one every 0.005 s.

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#### 4.2 PRNG Fallback

The PRNG is triggered when \texttt{rbg\_status} is set to \texttt{false}. The fallback function \texttt{rbg\_rand} is only triggered if the HRNG is available in general, as shown in Listing 3. The 4 B time register is increased by one every 0.005 s.

#### 4.3 Specification-Compliant Attacks

The only existing interface to acquire random numbers of the Bluetooth chip is the Host Controller Interface (HCI) command \texttt{LE\_Rand} \,[7, p. 2521]. After successful execution, this command is answered with an HCI event containing an 8 B random number. In theory, this could already be used on any off-the-shelf device to measure the RNG quality. However, the older variant (1), the \textit{Minimal PRNG Fallback}, is even worse. The fallback only performs a static calculation based on the current time, as shown in Listing 3. The 4 B time register is increased by one every 0.005 s.

### Table 2: HRNG test results.

| Chip                  | Device                  | Samples | Test         |
|-----------------------|-------------------------|---------|--------------|
| BCM4335C0             | Google Nexus 5          | 2.7 GB  |              |
| BCM43430A1            | Raspberry Pi 3/Zero W   | 1.3 GB  |              |
| BCM4345B0             | iPhone 6                | 1.8 GB  |              |
| BCM4355C0             | iPhone 7                | 1.0 GB  |              |
| BCM4345C0             | Raspberry Pi 3/4/       | 1.4 GB  |              |
| BCM4358A3             | Samsung Galaxy S6, Nexus 6P | 2.1 GB |              |
| CYW20719B1            | Evaluation board        | 1.4 GB  |              |
| CYW20735B1            | Evaluation board        | 1.6 GB  |              |
| CYW20819A1            | Evaluation board        | 1.2 GB  |              |
| BCM2046A2             | iMac Late 2009          | 2.5 GB  |              |
| BCM20703A1            | MacBook Pro early 2015  | 3.0 GB  |              |
| BCM4375B1             | Samsung Galaxy S10/S20  | 4.0 GB  |              |
| BCM4347B1             | iPhone 8/ X/ XR         | 5.0 GB  |              |
| BCM4378B1             | iPhone 11/ SE2          | 6.0 GB  |              |
We substitute the original \texttt{rbg\_rand} was using this memory area in parallel and is faster to insert 4096 measurements of 5 B values. After each 4 B returned by such a basic check out-of-the-box—reading chip memory and information. InternalBlue ready checking if aHRNG is present on a chip is an important given that the extensively tested HRNGs passed all tests, al-
comparably long and requires custom patches. However, and that the HRNGs in all chips passed the \textit{Dieharder} tem. Table 2 shows how much data was collected per chip one day, depending on the chip’s interface and operating sys-
tifications listed above, data collection takes approximately one day, depending on the chip’s interface and operating sys-
tem. Table 2 shows how much data was collected per chip and that the HRNGs in all chips passed the \textit{Dieharder} tests.

Each data extraction for the \textit{Dieharder} test suite still takes comparably long and requires custom patches. However, given that the extensively tested HRNGs passed all tests, already checking if a HRNG is present on a chip is an important information. InternalBlue implements everything required for such a basic check out-of-the-box—reading chip memory and
sending HCI commands. The hardware registers listed in Table 1 must contain one 4 B random number. This number is indeed the one used by the \texttt{rbg\_rand} function if it changes with actions like pairing. On devices supporting BLE, the HRNG can be triggered with the HCI command \texttt{LE\_Rand}. Firmware versions implementing a cache are required to get a call to \texttt{LE\_Rand} multiple times before the HRNG is used.

The second half of Table 2 contains devices from which we could not collect samples but that indeed have an HRNG. These devices include the \textit{iMac Late 2009}, the newest \textit{Samsung Galaxy S} series, and the \textit{iPhone 11} and \textit{SE}2. On the \textit{iMac Late 2009}, we were not able to program custom patches because RAM is very limited on that chip. Moreover, its inter-
face is slow 2, making it unrealistic to extract 1 GB of data. The \textit{Samsung Galaxy S}10 and S20 series use the same chip. However, \textit{Broadcom} improved firmware security and added stack canaries, which prevent calling functions out of context without additional modifications within our patches. As of now, there is no \texttt{InternalBlue} support for Peripheral Component Interconnect Express (PCIe) Bluetooth chips as on the most recent \textit{iPhone 11} and \textit{SE}2. Nonetheless, the chip can be tested with \texttt{BlueTool} on jailbroken iPhones. \texttt{BlueTool} is an Apple-internal tool included on \textit{iOS}. It is utilized for driver initialization, but it also has a rudimentary command-line interface with HCI support.

4.2 PRNG Measurements

The \textit{Samsung Galaxy S}8 series and an \textit{iPhone} are missing an HRNG. As there is a PRNG fallback, the firmware is still able to generate somewhat random numbers instead of being obviously broken for an outsider without firmware knowledge. Most likely the RNG test required to pass the specification did not include a firmware review, and, thus, only the checksummed

![Figure 2: Hardware clock (timer1value) and Bluetooth clock (dc_nbtc_clk) on the Samsung Galaxy S8.](image)

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2One specification-compliant HCI randomness event contains 8 B, while our events fill the maximum possible event payload of 251 B. The timing of HCI events is almost constant independent on their size. Assuming that our 251 B data extraction runs one day, the 8 B data extraction would require a month per device. The exact HCI speed depends on the \textit{InternalBlue} and host-specific implementation of each device.
combination of the registers the PRNG uses was measured.

The PRNG is accessing multiple hardware registers, listed in Table 3. While we do not have any symbols for the Samsung Galaxy S8 firmware, it is using the same registers as the BC20703A2 MacBook chip, and also the same code as previously shown in Listing 2.

We measure the PRNG registers with similar firmware modifications as for the HRNG measurements and also disable Wi-Fi. Over 1000 rounds, we store 4096 4 B values to the chip’s internal RAM. Then, we collect them via HCI. Due to the current InternalBlue implementation on Android 9, HCI introduces a delay, which is 3.075 s on average in our measurements. Thus, data about each register is collected over a time span of approximately 51 min. Each measurement round takes roughly 2.58 ms on the chip itself.

During the whole experiment, spurFreqErr1 and rxPsKPhErr5 stayed constant. The only non-clock hardware registers that changed are dc_fhout, rxInitAngle, and agcStatus. As shown in the histograms (Figure 3–6), these registers have very little variation. Moreover, they typically stay constant within one round and often even constant over multiple rounds. Figure 4 shows dc_fhout over time. In addition to the comparably slow change in its value, it also shows a pattern.

The clock registers dc_nbtc_clk and timer1value change, but they are also not random. The Bluetooth clock, dc_nbtc_clk, is shared over-the-air. This is required to keep connections synchronous. In addition, the current Bluetooth clock value is used in substantial parts of the protocol, i.e., as encryption algorithm input. As shown in Figure 2, the hardware and Bluetooth clock are aligned. However, the hardware clock has a 205 times higher granularity than the Bluetooth clock, meaning that even for a known Bluetooth clock and a hardware clock value that leaked once, future hardware clock values still have a slight variance.

Table 3: PRNG inputs on the Samsung Galaxy S8.

| Address  | Register   | Entropy                                                                 |
|----------|------------|-------------------------------------------------------------------------|
| —        | Rand       | Previous 4 B random value (leaks over-the-air)                          |
| 0x318088 | dc_nbtc_clk| Bluetooth clock, publicly available over-the-air                         |
| 0x32A004 | timer1value| Hardwate clock, 4 B “random” before first leak, unpachted attacks for clock reset available |
| 0x3186A0 | dc_fhout   | Changes a bit (0x00–0xmin)                                              |
| 0x410434 | agcStatus  | Changes a bit (0xc00 during whole measurement, slight changes within 0xc00 after reboot) |
| 0x41079C | rxInitAngle| Changes a bit but within similar range                                  |
| 0x4100AC | spurFreqErr1| Constant 2 B value (0x04ed, also after reboot)                           |
| 0x410548 | rxPsKPhErr5| Always 0                                                                |

Figure 3: Histogram of values of dc_fhout observed on a Samsung Galaxy S8.

Figure 4: dc_fhout over time on the Samsung Galaxy S8.

Figure 5: Histogram of values of rxInitAngle observed on a Samsung Galaxy S8.

Figure 6: Histogram of values of agcStatus observed on a Samsung Galaxy S8, two measurements, first one was constant 0xc00.
4.3 PRNG Attacks

All variants, including the newest variant 5, access the `rbg_rand` function in the same way. An overview of the calling structure is shown in Figure 7. How `rbg_rand` is used becomes relevant when attacking the PRNG. Attacks on the PRNG can be divided into predicting (Section 4.3.1) and influencing (Section 4.3.2) its inputs as well as extracting its current state (Section 4.3.3). Combining all of these provides the strongest attack vector. However, an attacker can opt to not actively manipulate the PRNG inputs, resulting in more bits to brute-force within random numbers or to infer the precise internal PRNG state. We describe how an attacker can predict PRNG outputs due to its weak implementation in Section 4.3.4.

4.3.1 Predicting PRNG Inputs

While some functions access `rbg_rand` directly, others use the wrapper `sha_get_128b_rand` that returns a 16 B random number. This wrapper calls `rbg_rand` 16 times in a row and applies the SHA-1 function. Note that SHA-1 is outdated and the Bluetooth specification recommends using SHA-256 within RNGs [7, p. 953]. Since the timing of subsequent calls in a loop is predictable, PRNG inputs that depend on time do not provide any additional entropy in this context. Moreover, `dc_fhout`, `rxInitAngle`, and `agcStatus` stayed constant within one measurement round in most cases, and, thus, also do not add any entropy except from the value in the first round.

4.3.2 Influencing PRNG Inputs

An attacker who has a crash-only over-the-air attack can reset the hardware clock to `0xFFFFFFFF`. Since the Patchram slots in the Broadcom and Cypress chips are rare, only severe security issues can be patched. Crash-only attacks, such as CVE-2019-6994, often remain unpatched [9]. The Bluetooth and hardware clock stay correlated over time, meaning that an attacker does not necessarily need to crash the chip while the user is pairing a new device or initiating an encrypted session, but any time before.

In addition to control and knowledge about the clock, a timed crash and following packet calling the PRNG might also set the current PRNG status to a less random value. The very first PRNG round is initialized by copying memory from RAM (see line 11 in Listing 2), which is likely filled with predictable contents during chip initialization.

4.3.3 Extracting PRNG Outputs

An attacker needs to know the current PRNG state including the previous random value `Rand` to get full knowledge about future PRNG values. Assuming that the firmware already accesses the PRNG a few times during initialization, even a chip reset might leave the attacker with some variability. Moreover, an attacker might not be able to reset the chip and, thus, does not have any knowledge about the internal PRNG state and needs to brute-force it.

All BLE-related functions access `ulp_rand`, which in turn calls `rbg_rand`. Thus, the LE_Rand HCI command allows direct access to the current RNG state.

However, an attacker typically acts over-the-air and does not have access to the host. The current state of the RNG can be leaked over-the-air as follows. An attacker can send an `LL_ENC_REQ` [7, p. 2898], which is answered with an `LL_ENC_RSP` [7, p. 2899]. The `LL_ENC_RSP` by the device under attack contains the fields SKDs and IVs. Within the firmware, these are generated by the functions `smulp_genSKD` and `smulp_genIV`, which both call `ulp_rand` that directly accesses the PRNG. This implementation is the same for the CYW20735B1 evaluation board, which is shown in the call graph in Figure 7, and the Samsung Galaxy S8.

Regarding the Samsung Galaxy S8, the Android implementation mentioned in Section 2.2 is vulnerable to passive MITM attacks. An attacker does not need to establish a connection and send an `LL_ENC_REQ` PDU—Android transmits the BLE RNG state within various packet types.

An attacker who inferred the current PRNG state and has knowledge or control about the hardware clock can calculate upcoming values provided by the PRNG.

4.3.4 Predicting PRNG Outputs

We will now describe how to predict randomness generated by the PRNG based on previous outputs. For each 4 B ran-
domness, the PRNG uses the previous output concatenated with the internal clock, the Bluetooth clock, and a number of registers. Then, it hashes them using a Cyclic Redundancy Check (CRC). Note that the input state consists of 32 B, therefore, it is infeasible to determine the full state based on outputs of the PRNG, even if we know that some of the values are not uniformly random. However, an attacker can exploit the fact that CRC32 is an affine function, using an initialization value of $IV = \text{0xFFFFFFFF}$. For two inputs $a$ and $b$,

$$\text{CRC32}(a) \oplus \text{CRC32}(b) = \text{CRC32}(a \oplus b) \oplus \text{CRC32}(IV).$$

Due to this affinity of CRC32, if we know the two previous outputs of the PRNG, we only need to guess the difference in the inputs to the PRNG. For the Bluetooth clock, we know its value as it is included in every transmission, and for the system clock, only the lowest bits will change with high probability. Further, as shown in the previous sections, the entropy in the other registers is quite low. Let $out_0$ and $out_1$ be the two previous outputs, then

$$out_2 = out_1 \oplus \text{CRC32}(C || R || P) \oplus \text{CRC32}(IV),$$

where $C$ is the guessed bit difference in both clocks, $R$ is the guessed bit difference in the registers, and $P$, the bit difference to the previous output field, is given by

$$P = \text{CRC32}(out_0) \oplus \text{CRC32}(out_1) \oplus \text{CRC32}(IV).$$

We estimate the difference entropy of the registers to be less than 18 bit. If we assume we have a synchronization between the Bluetooth clock and the hardware clock as described in Section 4.3.2, we need 8 bit for the hardware clock, resulting in a total of 26 bit. Note that further calls to the PRNG afterward are deterministic with high probability.

For example, for Numeric Comparison, we start by choosing a 128 bit random number $Nb$, which is generated by 16 successive calls to the PRNG. As we have shown in Section 2.1, the knowledge of $Nb$ would enable an MITM attack on the pairing process. Further, due to the deterministic commitment, we can check as an MITM attacker whether we found the correct $Nb$. A brute force attack to check all possible outputs of the PRNG would take about 5 min on a single CPU core. As this is trivially parallelizable, this is a realistic attack given enough computing power. Similar efficiency is to be expected in the case of generated private keys using randomness from the PRNG, as discussed in Section 2.2.

5 Discussion

Initially, we only measured the PRNG fallback on the Cypress evaluation boards and the Google Nexus 5. However, we found that the PRNG was not accessed during regular usage on those devices. Nonetheless, we suspected it being used in other chips due to the observed code changes, and, thus, reported it to Broadcom, Cypress, Apple, Google, and Samsung on January 12, 2020. We also informed the maintainer of BTstack [6] on the same date, because we observed that they were excessively using the HCI LE_Rand function during initialization of the Bluetooth stack for key generation. After a discussion with the BTstack maintainer, we decided to test if the PRNG was accessed on the Raspberry Pi 3B+ when constantly calling LE_Rand for more than a day, but luckily, the results were negative.

After this first round of responsible disclosure, Broadcom claimed that the PRNG fallback would not be used on any of their devices. This is when we started analyzing 20 different firmware versions. We informed Broadcom, Samsung, and Google about the missing HRNG in the Samsung Galaxy S8 on February 1, and also updated the others about the possibility that there are indeed chips without HRNG. Google closed the issue as Won’t Fix (Infeasible) on February 4, because it is up to Broadcom to fix the firmware and none of their products is affected. A patch for the Samsung Galaxy S8 as well as its variants S8+ and Note 8 was released in May.

There are a few iPhone models that we did not test, and the iOS 13.5 release contains a patch for a model that also missed a proper RNG. Since a test requires a jailbroken iPhone and we do not have all iPhone models available for testing, we could not identify the precise model and also could not perform any measurements. However, we performed tests for the registers used by the fallback on other devices and they provide similar properties as those on the Samsung Galaxy S8.

As Samsung is using Broadcom as well as Qualcomm chips on their smartphones, depending on the market and device model, they asked if they could forward our report. Since we did not find anything on Qualcomm chips ourselves and Qualcomm has an Non-Disclosure Agreement (NDA) with Samsung possibly allowing them to include confidential information, we asked Samsung to forward the report and exclude us if needed. We received the following answer on March 3:

“We haven’t found any indicators that our Bluetooth implementations are affected by the PRNG issue after internally discussing the research results that were shared with us.”

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What remains unclear is how the Samsung Galaxy S8 happened to miss an HRNG in the first place. The code for accessing the HRNG is already missing in the firmware, indicating that this issue was most likely known to developers during compilation—if not optimized and automated by another process. Yet, the BCM4347B0 chip made it into such a popular smartphone.
6 Conclusion

The development over a decade within the Broadcom and Cypress chips indicates that the RNG is indeed a central component. The firmware history shows how the PRNG fallback was first improved and then removed completely. However, removing it might also be harmful. If the PRNG fallback had been missing in the Samsung Galaxy S8, it might have simply returned static values.

Another interesting detail in the firmware history is that Cypress independently developed the PRNG code after acquiring the IoT branch of Broadcom in 2016 [11]. This indicates that also the patching process might differ depending on which company is assigned to which chip, even though the firmware has similar issues.

Overall, the RNG provided by a Bluetooth chip remains a black box without intensive analysis. The Bluetooth specification requires an RNG that passes tests such as the Dieharder test suite. This requirement leads to the potentially false assumption that a Bluetooth chip’s RNG can be trusted for security-relevant operations, including the HCI LE_Rand command exposing the RNG to energy-constrained embedded devices and the Android Bluetooth stack. Our RNG testing scripts are publicly available, allowing benchmarks of future or not yet tested Broadcom and Cypress chips as well as porting these concepts to chips of other manufacturers.

We tested many Bluetooth chips on our own. However, it would be helpful if manufacturers made details about the RNG openly accessible. During our research, we only found that the non-Bluetooth Broadcom main System on Chip (SoC) on the Raspberry Pi might include an HRNG that is based on thermal noise [12]. More transparency, i.e., statements whether a chip includes an HRNG or a PRNG and which type exactly, would be helpful when making design decisions on embedded and mobile devices.

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Availability

The RNG measurement assembler patches and scripts for the Broadcom and Cypress Bluetooth chips are openly available on GitHub. They are hosted as examples for InternalBlue on https://github.com/seemoo-lab/internalblue.

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