UEFI SECURE BOOT IN MODERN COMPUTER SECURITY SOLUTIONS

September 2013
Revised: August 2019

Authors:

Richard Wilkins, Ph.D.
Phoenix Technologies, Ltd.
Dick_Wilkins@phoenix.com

Brian Richardson
Intel Corporation
Brian.Richardson@intel.com

OVERVIEW

What is the UEFI Forum?

The Unified Extensible Firmware Interface (UEFI) Forum is a world-class non-profit industry standards body that works in partnership to enable the evolution of platform technologies. The UEFI Forum champions firmware innovation through industry collaboration and the advocacy of a standardized interface that simplifies and secures platform initialization and firmware bootstrap operations. Both developed and supported by representatives from more than 350 industry-leading technology companies, UEFI specifications promote business and technological efficiency, improve performance and security, facilitate interoperability between devices, platforms and systems, and comply with next-generation technologies.

What is UEFI Secure Boot, and how did it originate?

UEFI Secure Boot was created to enhance security in the pre-boot environment. UEFI Forum members developed the UEFI specification, an interface framework that affords firmware, operating system and hardware providers a defense against potential malware attacks. Without UEFI Secure Boot, malware developers can more easily take advantage of several pre-boot attack points, including the system-embedded firmware itself, as well as the interval between the firmware initiation and the loading of the operating system. Malware inserted at this point can provide an environment in which an operating system—no matter how secure—cannot run safely. Secure Boot helps firmware, operating system and hardware providers cooperate to thwart the efforts of malware developers. Additional background on the intent of UEFI Secure Boot can be found in "UEFI Networking and Pre-OS Security," published in the *Intel Technology Journal* [1].

What are the most common misperceptions about UEFI and UEFI Secure Boot?

Several misperceptions about UEFI Secure Boot, its intended uses, requirements and application exist within the technology and end-user community. A few of the most common are outlined below and in greater depth throughout this paper.

- **False:** "UEFI Secure Boot is an attempt to 'lock' platforms to software from specific vendors and block operating systems and software from others."
- **False:** "UEFI Secure Boot requires a TPM chip, as described by the Trusted Computing Group (TCG), and TCG controls the UEFI specification."
- **False:** "UEFI Secure Boot requires a specific implementation by computer manufacturers and operating system vendors."

CONTENTS

This paper discusses UEFI Secure Boot misperceptions and includes examples of potential malware attacks in the PC and non-PC space. It also provides history and examples of rootkit and bootkit attacks and outlines UEFI Secure Boot solutions. Below is a table of contents. *The views and opinions of the authors do not necessarily reflect the views of Phoenix Technologies and Intel Corporation, or their respective affiliates.*

MALWARE: FROM SIMPLE PRANKS TO SOPHISTICATED THREATS

Malware, or computer code written for nefarious purposes, has transitioned from the experiments and pranks of the 1980s to the sophisticated tools used today to intimidate, reduce productivity, and steal sensitive personal, financial or business information. As computer software developers have improved their resilience in the face of these attacks, malware developers have begun to target the firmware that starts up computer systems, focusing on the gap between the firmware and when the operating system starts. These are generally referred to as "rootkit" or "bootkit" attacks and will be explored in this paper.

BIOS HISTORY AND EMERGENCE OF UEFI SPECIFICATIONS

The firmware that initializes computer systems and loads an operating system is generally referred to as the BIOS (Basic Input/Output System). The term "BIOS" comes from the firmware developed for the IBM® PC/XT in the late 1970s [2]. That code was developed in assembly language for 16-bit 8086/8088 Intel™ processors and was targeted for use in a few thousand PC units. Despite inherent design limitations, that firmware implementation has been adapted and expanded many times.

In the late 1990s, Intel™ sought an alternative to BIOS for its new Itanium™ processor. Because the limitations of a 16-bit system caused problems on the newest 64-bit processor, the Extensible Firmware Interface (EFI) was developed as an alternative. The EFI design specified an interface between a firmware implementation on a hardware platform and on an operating system. As a result, either the platform firmware implementation or operating system implementation could change, but remain independent, as long as they followed the EFI specification. Intel released the EFI version 1.10 specification in 2002 [3].

The ownership of this specification was then transferred to the Unified EFI Forum, or UEFI Forum, a non-profit collaborative trade organization now made up of more than 50 promoting and contributing member companies and more than 350 adopting companies, formed to promote and manage the specification.

In November 2010, the UEFI Forum released a version of the UEFI specification [4] that included facilities for substantially enhanced security when booting operating systems. Modern UEFI specifications provide a standard and extensible interface between the firmware and the operating system. Additional background on UEFI can be

found in "Beyond BIOS: Exploring the Many Dimensions of the Unified Extensible Firmware Interface," in the *Intel Technology Journal* [5].

THE ADVENT OF ROOTKIT AND BOOTKIT ATTACKS

Malware developers have increased their attempts to attack the pre-boot environment because operating system, application and antivirus software vendors have been hardening their code and limiting security attack vectors. The two primary types of attacks in the firmware space are known as rootkits and bootkits. Malware hidden in the firmware is virtually untraceable by the operating system, unless a search specifically targets malware within the firmware. Malware in the firmware also has direct access to hardware components and can use Virtual Machine technology to compromise a system without the knowledge of the user or detection by the operating system. Moreover, some attacks attempt to implant themselves into the System ROM itself, meaning that if they succeed, they will persist even if the operating system is reinstalled or the hard drive is swapped out.

Firmware rootkits inject exploit code into the system, either by patching or replacing the default firmware image. Bootkits inject malicious code at the point where the firmware hands control over to the operating system, typically by modifying the operating system bootloader software. Rootkits and bootkits employ various methods to avoid detection, often targeting firmware because it is responsible for loading the operating system kernel.

The launch of Microsoft Windows® 8 increased awareness of UEFI specifications and heightened scrutiny of the boot process. Saferbytes S.r.l.s introduced Microsoft Windows 8-specific bootkits in September 2012 [6] and QuarksLab in April 2013 [7]. A similar demonstration against Mac OS X products occurred at Black Hat USA 2012 [8], though the Apple® products in question are based on an earlier EFI specification that predates current UEFI implementations. Therefore, these demonstrations did not occur under circumstances where UEFI Secure Boot was enabled.

The examples outlined above describe similar attack methods. The bootkit is deployed in the form of a UEFI executable, to masquerade as the default operating system boot loader. The bootkit then launches a patched version of the operating system loader, adding exploit code before the operating system loads malware protection. In the case of QuarksLab DreamBoot, the exploit code is applied to the Windows 8 loader in system memory, so the bootkit will not be detected by checking the boot loader for unapproved patches or modifications. The actual bootkit payload varies, since it is dependent on a specific operating system version.

Another bootkit variation attempts to capture user credentials required in the boot process. This type of attack is often referred to as the "evil maid attack," [9] describing a scenario in which someone installs the bootkit on a computer left unattended in an office or hotel room. The "evil maid attack" can be used to capture passwords for full disk encryption systems and other third-party security tools.

Attacking the operating system bootloader is not the only method employed for boot time exploits. Multiple security researchers have developed proof-of-concept attacks against Option ROM code attached to PCI Express (PCIe) peripherals. Examples from NISR at Black Hat 2007 [10] and Sogeti at HACK.LU 2010 [11] are based on Option ROM code for legacy BIOS systems, but the concept can also be applied to UEFI drivers. While Option ROM firmware is less accessible, these exploits are attractive because the code resides outside of the system firmware and can provide access to PCI resources (I/O, memory and DMA).

While rootkits and bootkits are an issue for any system, including legacy BIOS environments, they present a unique challenge to the UEFI ecosystem. The entire philosophy behind UEFI is to standardize and allow for extensibility of the pre-boot interface. While this openness and standardization can make the system vulnerable to attacks that

would have been more difficult in legacy BIOS, it is important to acknowledge that legacy BIOS had very limited provisions for detection or defense [12]. Any optimal solution for UEFI needs to embrace flexibility, while limiting attack vectors, mitigating risk, promoting possibilities and providing methods for manufacturers and users to control their security policy.

ATTACKS ON MOBILE and IoT DEVICES

The transition from traditional desktops and laptops to tablets and other mobile and Internet of Things (IoT) devices is changing the landscape of computing devices. Although these mobile and speciality devices have traditionally had a custom, locked-down environment, as they increase in power and versatility, they are employing UEFI firmware and are potentially subject to the same attacks.

These system attacks have grown in volume and complexity and may now be used by political entities to affect a nation's critical infrastructure [13]. While UEFI Secure Boot clearly cannot unilaterally "fix" the problem of cyber-attacks, it provides an important cross-functional solution across all platforms using UEFI firmware to limit the types of attacks described in this paper.

EXISTING FIRMWARE PROTECTION

Numerous existing specifications and software/hardware tools provide some protection to the pre-operating system environment.

The TCG and the complementary Trusted Platform Module (TPM), allow the firmware and operating system to take measurements of all phases of the booting process, as described in their PC Client Implementation Specification [14]. "Measured Boot," as this approach is called, can detect modified boot code, settings and boot paths, while providing sufficient information so a later agent can attest to the platform state after the boot process has been completed. This does not prevent an insecure boot from occurring. If malware modifies the boot process, that process will complete anyway, however, the measurements are available for the modification to be detected.

The United States Government—through the National Institute for Science and Technology (NIST), part of the Commerce Department—has released several guideline documents related to the security of the pre-boot environment. The following are examples.

NIST 800-147	BIOS Protection Guidelines [15]
NIST 800-147B	BIOS Protection Guidelines for Servers [16]
NIST 800-155	BIOS Integrity Measurement Guidelines [17]

While the NIST guidelines are valuable for platform security, they do not solve the issue of bootkit attacks.

- NIST 800-147 provides guidelines for desktop and laptop platform manufacturers and BIOS implementers on secure BIOS update mechanisms, ensuring the firmware may not be updated or replaced by an attacker. These guidelines, when followed, limit the possibility of successful firmware rootkits. NIST 800-147 is complementary to UEFI Secure Boot, as it protects the BIOS code in the System ROM from modification, while UEFI Secure Boot protects all other pre-operating system code in the system from malicious modification. Essentially NIST 800-147 reads on assurance, so that the underlying UEFI implementation is updated in a manufacturer-approved manner. Implementations of UEFI include but are limited to the UEFI Platform Initialization (PI) specification-based elements.

- NIST 800-147B mitigates threats to firmware in server-class systems. While this document is similar to NIST 800-147, it is focused on server systems instead of desktop and laptop systems deployed in enterprise environments.

- NIST 800-155 outlines a process using "measured boot" to provide a secure measurement and reporting chain, allowing an external server to detect and report unauthorized modifications to firmware or configuration. With this information, it may be possible for the server to initiate restrictions or remediation. This document is currently being updated by NIST in concert with the Trusted Computing Group (TCG)

These NIST guidelines provide a framework for limiting the possibility of improper firmware changes remaining undetected, as well as reporting any changes that occur, for later remediation. However, these guidelines do not seek to prevent an improperly modified system from running invalid code, potentially compromising the security of a user's data. The 800-155 standard does not prevent code from running, regardless of its state. Therefore, it is recommended to have Secure Boot in place for additional protection.

PROPOSED SOLUTION

Fundamentally, the UEFI Secure Boot [18] feature attempts to prohibit the execution of unprotected code prior to the engagement of the operating system. The NIST 800-147 guidelines attempt to prevent the core firmware of the system from being improperly modified. TCG "measured boot" and the NIST 800-155 guidelines attempt to detect systems that fail to boot securely. And yet, there are still a number of attack vectors that can allow a system to become operational in a compromised state. The Secure Boot and Driver Signing chapter of the UEFI specification provides a mechanism to minimize these attack vectors and thwart attacks.

Some members of the technology industry have raised the concern that the well-documented, modern, high-level language interface provided by UEFI makes it easier to compromise a platform [12]; that the ability to add modules and applications to the boot process could compromise security. Some have even postulated that it would be better to continue using legacy BIOS, with its old-style interface and assembly language requirements, as it would be more difficult for malware developers to access the code. However, it has long been demonstrated that "security through obscurity" provides little actual system protection [19]. Most authors of articles describing these vulnerabilities of the UEFI interfaces indicate that a solution like Secure Boot is needed to prevent these attacks.

The core issue is ensuring that a system boots without introducing compromised code. The solution is to start with a small core of code protected by a secure update process, as described by NIST 800-147. With a secure starting point, the next step is to confirm that each subsequently-executed section of code is safe and unmodified before it is executed. If it is not safe and unmodified, UEFI Secure Boot aims to ensure that it will not be executed.

UEFI SPECIFICATIONS' UTILITY WHEN EXECUTING BOOT CODE

Ensuring that boot code is executed without modification requires the use of a digital signature. A digital signature, provided by a trusted code creator, is embedded in every executable code section. Using public/private key pairs, the code creator "signs" their code with a private key, which can be checked against a public key in a pre-stored signature before it is executed. If the executable has been modified or marked as invalid, then it is not executed in the boot path. The system may take an alternate boot path, or the user may be notified and can take remedial actions. It is important to note that a compromised system is typically not allowed to complete the bootstrap process in a compromised state.

The Secure Boot chapter of the UEFI specification focuses on the mechanisms for signing code images and managing keys and signatures. Secure Boot is an optional UEFI feature. The way it is managed, enabled or disabled is a decision of the platform manufacturer and the system owner. Throughout the specification, UEFI Forum contributors have made a deliberate effort to provide security-enhancing interfaces and mechanisms, while also allowing implementers to specify how they are used.

MANAGEMENT OF KEYS AND SIGNATURES IN CODE EXECUTION

A series of keys and databases are used to manage and protect the signatures needed to verify code before it is executed. First, there is the Platform Key (PK). This key is typically set by the platform manufacturer when a system is built in the factory. While it may be replaceable by an end user or enterprise IT services, its purpose is to protect the next key from uncontrolled modification.

The second key is the Key Exchange Key (KEK), which protects the signature database from unauthorized modifications. No changes can be made to the signature database without the private portion of this key. There can be multiple KEKs provided by the operating system and other trusted third party application vendors. A holder of a valid KEK can insert or delete signatures in a signature database. The database maintains two lists of signatures: signatures of code that is authorized to run on the platform and signatures of code that is forbidden.

As the boot process proceeds from an initial protected firmware core, it will load and execute additional sections of code, drivers and Option ROMs (code provided by peripheral manufacturers to enable their devices). Eventually this process culminates in the loading and execution of the operating system boot loader that starts the operating system execution. As each code section is loaded, and before it is executed, the firmware confirms that its signature matches one in its database of authorized signatures, and also that the signature is not in the forbidden database. This includes the operating system boot loader itself. What the firmware does with the signature matching information is a policy decision, and is not defined by the specification. Typically, unauthorized code will not be executed, and therefore, the system may not be able to complete the operating system bootstrap process.

In this way, a user is protected from running a compromised system and may be able to take remedial actions to remove the compromised code from the boot process and restore the system to normal operation. This feature complements the NIST guidelines for securing firmware updates (800-147/800-147B), as well as the TCG/NIST approach for measured boot and remote attestation of a successful and secure boot (800-155).

SECURE BOOT AS AN OPTIONAL FEATURE

Secure Boot is an optional feature of the UEFI specification. The choice of whether to implement the feature and the details of its implementation (from an end-user standpoint) are business decisions made by Original Equipment Manufacturers (OEMs). As of this date, no one has claimed or demonstrated an attack that can circumvent UEFI Secure Boot on a system on which it is properly implemented and enabled[1].

For specialized equipment like kiosks, tablets, phones or IoT devices, operating in constrained environments, a manufacturer may choose to implement Secure Boot and not provide users with any control interfaces. In contrast, typical personal computer systems provide users more control.

---

[1] While it may be possible to circumvent UEFI Secure Boot on some machines [21], this is due to errors in implementation—as opposed to a security flaw of UEFI.

Many companies, including Microsoft, contributed to the development of the UEFI Secure Boot feature. The launch of Microsoft Windows 8 increased system security and required that computer manufacturers enable the feature by default and include Microsoft keys and signatures.

DISABLING SECURE BOOT

Options typically exist for disabling UEFI Secure Boot, as well as for using it with operating systems other than Microsoft Windows 8. If a personal computer user chooses not to use Secure Boot, they may use the following options to disable it.

Users may disable Secure Boot entirely, using a system setup screen enabled at boot time. Each manufacturer has its own interface for this option. In all cases, end user must be physically present to establish proof of possession (POP) associated with the changes. With the Secure Boot feature disabled, the system can boot legacy operating systems, as well as systems that do not support Secure Boot. However, when Secure Boot is disabled, the feature is no longer protecting the system, leaving it vulnerable to rootkit and bootkit attacks.

UEFI Secure Boot also provides an interface that allows a system owner to take control of the system's security credentials. This interface may or may not be available, depending on the system and its manufacturer. In circumstances where it is available, system owners can clear and reinstall the Secure Boot database and register their own keys and signatures. This can either supplement or completely replace the factory set. If a particular system supports the clearing of Secure Boot databases, the option will be displayed in the firmware menus.

TRUSTED SIGNERS

The Secure Boot database is initialized with a list of trusted signers at the Original Equipment Manufacturer's (OEM) factory that identifies entities trusted to sign Option ROMs, bootloaders, drivers and applications. Instead of requiring a unique certificate from every possible trusted company, a centralized Certificate Authority (CA) is used. Microsoft announced a program that allows industry companies to submit binaries for signing by a Microsoft UEFI CA. The certificate for this CA is provided to OEMs for inclusion at the factory. As use of Secure Boot expands into various new segments, additional CAs may be established to serve these environments.

If they choose, Linux users can select operating system distributions created by developers who have elected to provide initial bootloaders signed by Microsoft's CA, which establishes the verification of a trusted relationship. Several Linux distributions have provided users with a general-purpose pre-bootloader that will chain boot to the standard Linux bootloader in a secure manner [20]. This process extends the benefits of UEFI Secure Boot to the Linux system environment.

BEYOND SECURE BOOT

Secure Boot itself is only part of an overall security solution. It may be combined with a TPM chip on the motherboard to securely store critical credentials, though this is not a requirement of Secure Boot. UEFI Secure Boot can also work with measured boot to detect how and where improper modifications have been made to a system, as described by the Trusted Computing Group [14]. UEFI Forum members continue to work on security improvements, simplifying secure features from platform manufactures and software vendors.

CONCLUSION

The potential for system security to be compromised via rootkits or bootkits has been present since the dawn of the personal computer. As other avenues of attack have been limited and system firmware technology has become more flexible and robust, the pre-boot arena has become a prime target. UEFI Secure Boot was created to make systems less vulnerable to these types of attacks.

The increasing complexity and variety of attacks makes it unwise to allow all users full administrative privileges at all times. Allowing all users unvetted access would cause their systems to be vulnerable to simple macro viruses downloaded from an email, or from a compromised website. In the same way, disabling Secure Boot and leaving a system unprotected from hard-to-detect rootkits and bootkits is also not recommended.

While no single technology can eliminate all security risks, even in the small window of the pre-operating system space, the use of UEFI Secure Boot—along with secure firmware update techniques and measured boot—limits the opportunity for malware developers to attack a system before anti-malware software can be enabled.

REFERENCES

[1]   Nystrom, et al, "UEFI Networking and Pre-OS Security," in *Intel Technology Journal - UEFI Today: Boostrapping the Continuum*, Volume 15, Issue 1, pp. 80-101, October 2011, ISBN 978-1-934053-43-0, ISSN 1535-864X.
http://noggin.intel.com/sites/default/files/tech_journal_full_pdfs/intelr_technology_journal_volume_15_issue_1_2011.pdf

[2]   IBM, "IBM Personal Computer XT Technical Reference," January 1983.

[3]   Intel, "Extensible Firmware Interface Specification V1.10," ed: Intel, 2002.

[4]   UEFI, "UEFI Specification Version 2.2," ed, 2010.

[5]   Doran, et al, "Beyond BIOS: Exploring the Many Dimensions of the Unified Extensible Firmware Interface," in *Intel Technology Journal - UEFI Today: Boostrapping the Continuum*, Volume 15, Issue 1, pp. 8-21, October 2011, ISBN 978-1-934053-43-0, ISSN 1535-864X

[6]   A. Allievi. (2012, May 13, 2013). UEFI technology: say hello to the Windows 8 bootkit! Available:
http://www.saferbytes.it/2012/09/18/uefi-technology-say-hello-to-the-windows-8-bootkit/

[7]   S. Kaczmarek, "UEFI and Dreamboot," presented at the Hack in the Box Security Conference, Kuala Lumpur, Malasia, 2013.

[8]   L. K, "DE MYSTERIIS DOM JOBSIVS Mac EFI Rootkits," presented at the Black Hat USA 2012, Las Vegas, NV 2012.

[9]   D. Danchev. (2009, May 13, 2013). 'Evil Maid' USB stick attack keylogs TrueCrypt passphrases. *ZDNet*. Available: http://www.zdnet.com/blog/security/evil-maid-usb-stick-attack-keylogs-truecrypt-passphrases/4662

[10]   J. Heasman, "Implementing and Detecting a PCI Rootkit," presented at the Black Hat DC 2007, 2006.

[11]   G. Delugre, "Closer to metal: Reverse engineering the Broadcom NetExtreme's firmware," presented at the HACK.LU 2010, Luxembourg, 2010.

[12]   J.-F. Agneessens. (2012, Analysis of the building blocks and attack vectors associated with the Unified Extensible Firmware Interface (UEFI). Available:
https://www.sans.org/reading_room/whitepapers/services/analysis-building-blocks-attack-vectors-unified-extensible-firmware_34215

[13]   J. A. Lewis, "Assessing the Risks of Cyber Terrorism, Cyber War and Other Cyber Threats:," Center for Strategic and International Studies December 2002.

[14]   T. C. Group, "TCG PC Client Specific Implementation Specification for Conventional BIOS," ed, 2012.

[15]   D. Cooper, W. Polk, A. Regenscheid, and M. Souppaya, "BIOS Protection Guidelines (NIST 800-147)," National Institute of Standards and Technology, April 2011.

[16]   A. Regenscheid, "BIOS Protection Guidelines for Servers (NIST 800-147B)," National Institute of Standards and Technology, July 2012.

[17]   A. Regenscheid and K. Scarfone, "BIOS Integrity Measurement Guidelines (NIST 800-155)," National Institute of Standards and Technology, December 2011.

[18]   UEFI, "Unified Extensible Firmware Interface Specification, Version 2.3.1c," ed, 2011.

[19]   P. P. Swire, "A Theory of Disclosure for Security and Competitive Reasons: Open Source, Proprietary Software, and Government Agencies," *Houston Law Review,* vol. 42, January 2006.

[20]   J. Bottomley. (2012, May 22, 2013). Linux Foundation UEFI Secure Boot System for Open Source. *Linux Foundation Blogs*. Available: http://www.linuxfoundation.org/news-media/blogs/browse/2012/10/linux-foundation-uefi-secure-boot-system-open-source

[21]   Yuriy Bulygin, Andrew Furtak and Oleksandr Bazhaniuk."A Tale of One Software Bypass of Windows 8 Secure Boot." Black Hat 2013. Available: http://www.c7zero.info/stuff/Windows8SecureBoot_Bulygin-Furtak-Bazhniuk_BHUSA2013.pdf