Wisecr: Secure Simultaneous Code Dissemination to Many Batteryless Computational RFID Devices

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Abstract—Emerging ultra-low-power tiny scale computing devices run on harvested energy, are intermittently powered, have limited computational capability, and perform sensing and actuation functions under the control of a dedicated firmware operating without the supervisory control of an operating system. Wirelessly updating or patching firmware of such devices is inevitable. We consider the challenging problem of simultaneous and secure firmware updates or patching for a typical class of such devices—Computational Radio Frequency Identification (CRFID) devices. We propose Wisecr, the first secure and simultaneous wireless code dissemination mechanism to multiple devices that prevents malicious code injection attacks and intellectual property (IP) theft, whilst enabling remote attestation of code installation. Importantly, Wisecr is engineered to comply with existing ISO compliant communication protocol standards employed by CRFID devices and systems. We comprehensively evaluate Wisecr’s overhead, demonstrate its implementation over standards compliant protocols, analyze its security, implement an end-to-end realization with popular CRFID devices and open-source the complete software package on GitHub.

Index Terms—RFID, Computational RFID, WISP, ISO 18000-63 Protocol, EPC Protocol, Secure Wireless Firmware Update.

1 INTRODUCTION

The maturation of energy-harvesting technology and ultra-low-power computing systems is leading to the advent of intermittently-powered, batteryless devices that operate entirely on energy extracted from the ambient environment. The batteryless, low cost simplicity and the maintenance free perpetual operational life of these tiny scale computing platforms provide a compelling proposition for edge devices in the Internet of Things (IoT) and Cyber-Physical Systems.

Recent developments in tiny scale computing devices such as Wireless Identification and Sensing Platform (WISP) and Farsens Pyros, or so called Computational Radio Frequency Identification (CRFID) devices, are highly resource limited, intermittently-powered, batteryless and operate on harvested RF (radio-frequency) energy. CRFID type devices are more preferable in scenarios that are challenging for traditional battery-powered sensors, for example, pacemaker control and implanted blood glucose monitoring, as well as domains where batteries are undesirable, for example, wearables for healthcare applications. While, significant industrial applications are exemplified by asset management, such as monitoring and control of an operating system. Wirelessly updating or patching firmware of such devices is inevitable. In the absence of standard protocols or system level support, firmware is typically updated using a wired programming interface. In practical applications, the wired interface results in a potential attack vector to tamper with the behavior of the devices and a compromised device can be further hijacked to attack other networked entities. Disabling the wired interface after the initial programming phase at manufacture can prevent further access. But, leaves the wireless update option as the only method to alter the firmware or to re-purpose the devices post-manufacture.

Fig. 1. (a) An attacker may: i) commit a malicious code injection attack such as alter code to inject bugs or load unauthorized code; ii) attempt to prevent a new firmware installation and spoof the acknowledgment signal of a successful update; and iii) commit IP theft by exploiting the insecure wireless channel. (b) A typical device architecture where the amount of power available for harvesting decreases exponentially with distance \( d \) from a powering source.

However, point-to-point communications protocols over limited bandwidth communication channels characteristic of RFID systems poses problems for rapid and secure update of firmware over a wireless interface, post-manufacture. Notably, Federal Aviation Administration (FAA) in the United States has granted the installation of RFID tags and sensors on airplanes in 2018, an increasing number of CRFID sensors are integrated with small aircraft and commercial airliners for maintenance history logging and aircraft

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health monitoring [9]. In such a scenario, a high-efficiency (simultaneous) and secure firmware update is desirable to ensure operational readiness and flight safety.

The recent Stork [7] protocol addressed the challenging problem of fast wireless firmware updates to multiple CRFID devices. But, as illustrated in Fig. 1, Stork allows any party, authorized or not, armed with a simple RFID reader to: i) mount malicious code injection attacks; ii) attempt to spoof the acknowledgment signal of a successful update to fool the Server; and iii) steal intellectual property (IP) by simply eavesdropping on the over-the-air communication channel. Although a recent protocol [17] addressed the problem of malicious code injection attacks where by a single CRFID device is updated in turn, it neither supports simultaneous updates to many devices nor protects firmware IP and lacks a mechanism to validate the installation of code on a device.

Why Secure Wireless Firmware Update is Challenging?

Constructing a secure wireless firmware update mechanism for ultra-low power and batteryless devices is non-trivial; designing a secure method is challenging. We elaborate on the challenges below.

**Limited and indeterminate powering.** Energy-harvesting systems operate intermittently, only when energy is available from the environment. To operate, a device gradually buffers energy into a storage element (capacitor). Once sufficient energy is accumulated, the device begins operations. However, energy depletes more rapidly (e.g. milliseconds) during an operation compared to energy accumulation/charging (e.g. seconds). Further, energy accumulation in RF energy harvesting is sacrificed in backscatter communication links since a portion of the incident energy is reflected back during communications. Therefore, power failures are common and occur in millisecond time scales [7], [18], as experimentally validated in Fig. 2.

Timing of power loss events across devices are ad-hoc. For example, harvested energy varies under differing distances; therefore, a computation task may only execute partially before power failure and it is hard to predict when it will occur.

Further, saving and subsequently retrieving state at code execution checkpoints for a long-run application via an intermittent execution model [20] is not only: i) costly in terms of computations and energy [21]—saving state in non-volatile memories such as Flash or Electrically Erasable Programmable Read-Only Memory (EEPROM) consumes more energy than static RAM (SRAM) whilst reading state from Ferroelectric Random Access Memory (FRAM) consumes more energy than writing as we demonstrate in Fig. 5 but also: ii) renders a device in a vulnerable state for an attacker to exploit when checkpoint state is stored on an off-chip memory, due to the lack of internal MCU memory, where non-invasive contact probes can be used to readout contents when the memory bus used is easily accessible [22]. For example, common memory readout ports such as the I²C (Inter-Integrated Circuit) bus used by a microcontroller for connecting to external memory devices are often exposed on the top layer of a printed circuit board (PCB). Hence, the content stored in an off-chip NVM can be easily read out using contact probes without any damage to the hardware [23].

These issues make the execution of long-run security algorithms, such as Elliptic Curve Diffie-Hellman (ECDH) key exchange, difficult to deploy securely.

Consequently, power must be carefully managed to avoid power loss and leaving the device in a potentially vulnerable state; and, we must seek computationally efficient security schemes.

**Unavailability of hardware security support.** Highly resource-constraint devices lack hardware security support. Thus, security features, including a trusted execution environment (TEE)—for example, ARM Trustzone [26] and dedicated memory to explicitly maintain the secrecy of a long term secret keys, as in [27], are unavailable.

**Constrained air interface protocols.** The widely used wireless protocol for Ultra High Frequency (UHF) RFID communication only provides insecure unicast communication links and supports no broadcast features or device-to-device communication possible in mesh networking typical of wireless sensor networks.

**Unavailability of supervisory control from an operating system.** Unlike wireless sensor network nodes, severely resource limited systems, such as CRFID, do not operate under the supervisory control of an operating system to provide security or installation support for a secure dissemination scheme.

### 1.1 Our Study

We consider the problem of secure and simultaneous code dissemination to multiple RF-powered CRFID devices operating under constrained protocols, device capability, and extreme on-device resource limitations—computing power, memory, and energy.

The scheme we developed overcomes the unique challenges, protects the firmware IP during the dissemination

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1. We are aware of optimized public key exchange implementations such as ECDH and Ring-LWE [24], [25]; however, they are impractical for passively powered resource-constrained devices. For example, ECDH [24] with Curve25519 still requires 4.88 million clock cycles on a MSP430 MCU. In contrast, there are a very limited number of clock cycles available from harvested-energy before energy depletion [7], [18]—e.g. 400,000 clock cycles expected even at close proximity of 50 cm from an energy source, see Fig. 2—and there is very limited time available for computations where a CRFID must reply before strict air interface protocol time-outs are breached.
process, prevents malicious code injection attacks and enables remote attestation of code installation. More specifically, we address the following security threats:

- **Malicious code injection**: code alteration, loading unauthorized code, loading code onto an unauthorized device, and code downgrading.
- **Incomplete firmware installation**
- **IP theft**: reverse engineering from plaintext binaries.

Consequently, we fulfill the **urgent** and **unmet** security needs in the existing state-of-the-art multiple CRFID wireless dissemination protocol—Stork [7].

1.2 Our Contributions and Results

**Contribution 1 (Section 2)**—**Wisecr** is the first secure and simultaneous (fast) firmware dissemination scheme to multiple batteryless CRFID devices. **Wisecr** provides three security functions for secure and fast updates: i) preventing malicious code injection attacks; ii) IP theft; and iii) attestation of code installation. **Wisecr** achieves rapid updates by supporting simultaneous update to multiple CRFID devices through a secure broadcasting of firmware over a standard non-secure unicast air interface protocol.

**Contribution 2 (Section 3 & 4)**—A holistic design trajectory, from a formal secure scheme design to an end-to-end implementation requiring only limited on-device resources. Ultra-low power operating conditions and on-device resource limitations demand both a secure and an efficient scheme. First, we built an efficient broadcast session key exchange exploiting commonly available hardware acceleration for crypto on microcontroller units (MCUs).

Second, to avoid power loss and thus achieve uninterrupted execution of a firmware update session, we propose new methods: i) adaptive control of the execution model of devices using RF powering channel state information collected and reported by field deployed devices; ii) reducing disruptions to broadcast data synchronization across multiple devices by introducing the concept of a pilot tag selection from participating devices in the update scheme to drive the protocol. These methods avoid the need for costly, secure checkpointing methods and leaving a device in a vulnerable state during power loss.

Third, in the absence of an operating system, we develop an immutable bootloader to: i) supervise the control flow of the secure firmware update process; ii) minimize the occurrence of power loss during an update session whilst abandoning a session in case an unpreventable power loss still occurs; and iii) manage the secure storage of secrets by exploiting commonly available on-chip memory protection units (MPUs) to realize an immutable, bootloader-only accessible secrets.

**Contribution 3 (Section 5 and Appendix 5)**—ISO Standards compliant end-to-end **Wisecr** implementation. We develop **Wisecr** from specification, component design to architecture on the device, and implementation. We evaluate **Wisecr** extensively, including comparisons with current non-secure methods, and validate our scheme by an end-to-end implementation. **Wisecr** is a standard compliant secure firmware broadcast mechanism with a demonstrable implementation using the widely adopted air interface protocol—ISO-18000-63 protocol albeit the protocol’s lack of support for broadcasting or multi-casting—and using commodity devices from vendors. Hence, the **Wisecr** scheme can be adopted in currently deployed systems. We demonstrate the firmware dissemination process here: [https://youtu.be/GgDHPJi3A5U](https://youtu.be/GgDHPJi3A5U)

**Contribution 4**—Open source code release. The tool sets and end-to-end implementation is open-sourced on GitHub: [https://github.com/AdelaideAuto-IDLab/Wisecr](https://github.com/AdelaideAuto-IDLab/Wisecr)

**Paper Organization.** Section 2 presents the threat model, security requirements and **Wisecr** design; Section 3 details how the demanding security requirements are met under challenging settings; Section 4 discusses our end-to-end implementation, followed by performance and security evaluations; Section 5 discusses related work with which **Wisecr** is compared. Section 6 concludes this work.

2 **Wisecr Design**

In this section, we describe the threat model including a summary of notations in Table 1 followed by details of **Wisecr** design, and then proceed to identify the minimal hardware security requirements needed to implement the scheme.

| Table 1. Table of Notations |
|----------------------------|
| **S** | Server S is a single entity consisting of a host computer and a networked RFID reader. |
| **T** | Tokens T is a set of individual (CRFID) devices \( T_i \). |
| **DB** | Server’s database, where each element is a three-tuple describing each CRFID token: i) the unique and immutable identification number \( \text{id} \); ii) the device specific secret key \( k \); and iii) a flag denoting a device requiring an update valid. |

**firmware** The new firmware binary for the update.

**firmware\((j)\)** The \( j_{th} \), block of the firmware.

**nver** The new version number (a monotonically increasing ordinal number with a one-to-one correspondence with each updated firmware).

**ver** A token’s current version number.

**sk** The broadcast session key.

**c, r** Attestation challenge and response, respectively.

\( \square \) An apostrophe denotes a value computed by a different entity, e.g. \( s' \) the MAC tag computed by a Token.

\( \square_i \) A subscript \( i \) denotes a specific entity, e.g., \( k_i \) is the device key of the \( i_{th} \) Token.

\( \square_i \) Encrypted data, e.g. (sk) denotes the encrypted session key sk, with the \( i_{th} \) token’s key \( k_i \).

**RNG()** A cryptographically secure random number generator.

**SKP.Enc()** Symmetric Key Primitive encryption function described by \( (m) \leftarrow \text{SKP.Enc}(m) \). Here, the plaintext \( m \) is encrypted with the sk to produce the ciphertext \( (m) \).

**SKP.Dec()** Symmetric Key Primitive decryption function where \( m \leftarrow \text{SKP.Dec}(\text{sk}(m)) \).

**MAC()** Message Authentication Code function. By appending an authentication tag \( s \) to the message \( m \), where \( s \leftarrow \text{MAC}(m) \), a message authentication code (MAC) function can verify the integrity and authenticity of the message by using the symmetric key \( k \).

**SNIFF()** The voltage \( V_{t} \) established by the power harvester within a fixed time \( t \) from boot-up at token \( i \), is measured by **SNIFF()** described by \( V_{t} \leftarrow \text{SNIFF}(t) \).

**PAM()** Family of functions employed by the Power Aware Execution mode of operation proposed for the token to mitigate power-loss (brown-out) events.

**Query** We denote **EPC Gen2** commands using typewriter fonts.
2.1 Threat Model

Communication with an RFID device operating in the UHF range is governed by the widely adopted ISO-18000-63:2015—also known as the EPCglobal Class 1 Generation 2 version 2 (C1G2v2)—air interface protocol or simply the EPC Gen2.

Our focus is on the insecure communication channel between the RFID reader connected antenna and the CRFID devices energized by the antennas. The reader network interface is accessed by using a Low-Level Reader Protocol (LLRP) from a host computer and a reader are considered as a single device; this region is inaccessible to the firmware (application) stored in NVM that is read-only accessible by the immutable bootloader. The device specific secret key stored in NVM that is read-only accessible by the immutable bootloader. The division of firmware is specified in the EPC Gen2 protocol (i.i.d.); iii) different devices are assumed to be independent and identically distributed (i.i.d.); iii) version number (version). The secure storage area is only accessible by the trusted and immutable bootloader provisioned on the device; this region is inaccessible to the firmware (application) and therefore cannot be modified by it.

We describe a dissemination session in four stages: i) Prelude; ii) Security Association; iii) Secure Broadcast; and iv) Validation. An update can be extended with an optional, v) Remote Attestation to verify the firmware installation.

STAGE 1: Prelude (Offline). In this stage, the Server S undertakes setup tasks. The Server uses $\text{RNG}(\cdot)$ to generate a broadcast session key (sk).

The new firmware is divided into segments—or block; each block $j$ is encrypted as $\left<\text{firmware}^{(j)}\right> \leftarrow \text{SKP.Enc}_{sk}(\text{firmware}^{(j)})$, where $\left<\text{firmware}^{(j)}\right>$ is the encrypted firmware block $j$. The division of firmware is necessary as the narrow band communication channel and

![Diagram](image.png)

Fig. 3. (a) System overview. (b) Control/data flow over the EPC Gen2 air interface. Firmware update will take place once a device enters the Access state and by implementing Wisecr over Access command specifications such as Authenticate.
the EPC Gen2 protocol does not allow arbitrary size payloads to be transmitted to a token.

**STAGE 2: Security Association.** In this stage, the Server $S$ distributes the broadcast session key $(sk)$ to all tokens $T$ and builds a secure broadcast channel over which to simultaneously distribute the firmware to multiple tokens.

More specifically, each token in the energizing field of the Server responds with id$_i$, Vt$_i$ and ver$_i$. The token will not be included in the following update session if: i) the id$_i$ of the responding token is not in Server’s DB; or ii) the token is not scheduled for an update (valid$_i$ = False). For tokens selected for an update, the Server computes a MAC tag $s_i = \text{MAC}_k(\text{firmware}||\text{ver}||\text{nver})$. In practice, we cannot assume that each token is executing the same version of the firmware, therefore a token specific MAC tag is generated over the device specific key whilst the firmware is encrypted with the broadcast session key.

The Server establishes a shared session key with each token $T_i$ by sending $(sk_i)$, where $(sk_i) \leftarrow \text{SKPEnc}_k(sk)$ and $k_i$ is specific to the $i_{th}$ token, and nver$_i$. The $(sk_i)$ and $s_i$ are transmitted to each token $T_i$. Each token decrypts the broadcast session key $sk \leftarrow \text{SKPDec}_k((sk_i))$—thus, all tokens selected for an update now possess the session key.

Notably, as detailed in Section 3.2.2, each token measures its powering channel state or its ability to harvest energy by measuring the voltage Vt$_i$ established by the power harvester within a fixed time $t$ from boot-up, as Vt$_i \leftarrow \text{SNIFF}(t)$ to transmit to the Server. There are two important reasons for measuring Vt$_i$: First, to facilitate the power aware execution model (PAM) employed to mitigate power-loss at a given token. The Server uses the reported Vt$_i$ to control the execution model of the $i_{th}$ token. Specifically, the reported Vt$_i$ is used by the Server to determine the length of time that a token dwells in low power mode (LPM) $t_{LPM}$, and active mode $t_{active}$, when executing computationally intensive tasks in the Secure Broadcast and Validation stages; here, the server determines $(t_{LPM}, t_{active}) \leftarrow \text{PAM.Get}(Vt_i)$. Second, the Server uses the reported Vt$_i$ to realize the Pilot-Observer Mode of operation where one token is elected based on its Vt$_i$, termed the Pilot, to control the flow in the Secure Broadcast stage by responding to server commands as detailed in Stage 3.

**STAGE 3: Secure Broadcast.** In this stage, the encrypted firmware blocks $(\text{firmware}^{(1..n)})$ are broadcasted; and each token stores the new encrypted firmware blocks in its application memory region (Segment $M$ defined in Section 3.1). Once the broadcast is completed, each token starts firmware decryption and validation. The $(\text{firmware})$ is decrypted using the session key $sk$ as $\text{firmware}^{(i)} \leftarrow \text{SKP.Dec}_k((\text{firmware}^{(i)}))$.

To realize a secure and power efficient logical broadband channel under severely energy constrained settings, we use the Pilot-Observer mode. Herein, all tokens, except the Pilot token elected by the Server, enters into an observer mode. The tokens in the observer mode silently listen and store encrypted data disseminated by the server; the Pilot token performs the same operation whilst responding to the server commands. We employ two techniques within the Pilot-Observer Mode to mitigate power-loss and to achieve a secure broadcast to tokens: i) disabling energy consuming communication command reply from observers; and ii) the
concept of electing a Pilot CRFID device to drive the update session as detailed in Section 3.2.2.

Notably, the techniques described in Stage 2 and 3 form the foundation for the uninterrupted execution of the bootloader to ensure security and enhance the performance of the firmware dissemination under potential power-loss events.

STAGE 4: Validation. In this stage, firmware is validated before installation. More precisely, a token specific MAC tag $s'_i \leftarrow \text{MAC}_k(\text{firmware}\|\text{id}_i\|\text{ver}_i)$ is computed by each token $T_i$. If the received MAC tag $s_i$ matches the device computed $s'_i$, the integrity of the firmware established and the issuing Server is authenticated by the token. Subsequently, the new firmware is updated and the new version number $\text{ver}_i$ is stored as $\text{ver}_i$. Otherwise, the firmware is discarded and the session is aborted. Notably, the EPC Gen2 protocol provides a reliable transfer feature. Each broadcast payload is protected by a 16-bit Cyclic Redundancy Check (CRC-16) error detection method. Hence, the notification of a CRC failure to the Server results in the automatic retransmission of the packet by the Server. Therefore, a MAC tag mismatch is more likely to be adversarial and discarding the firmware is a prudent action. At stage completion, each token switches from the observer or Pilot to the normal mode of operation after a software reset (reboot). Subsequently, all the temporary information such as session key $sk$ and the token specific MAC tag $s'_i$ in volatile memory will be erased.

Once the firmware is installed, the Server is acknowledged with the status of each participating token in the session. This is achieved by performing an EPC Gen2 handshake after a reboot of the tokens, and comparing the version number $\text{ver}_i$, reported from each token specified by $\text{id}_i$, to the new firmware version number $\text{ver}_i$ expected from the token. If the $\text{ver}_i$ is up-to-date, the Server is acknowledged that the token $T_i$ has been successfully updated.

Remark. It is theoretically possible to include a MAC tag in the acknowledgment message at the end of the Validation stage to authenticate the acknowledgment. But the implementation of this in practice is difficult under constrained protocols and limited resources typical of intermittently powered devices. This is indeed the case with the EPC Gen2 air interface protocol and CRFID devices we employed. We discuss specific reasons in Appendix B where we detail implementation of the Wisecr Update Scheme over the EPC Gen2 air interface protocol.

STAGE 5 (Optional): Remote Attestation.

The Server can elect to verify the firmware installation on a token by performing a remote attestation; a mechanism for the Server to verify the complete and correct software installation on a token. Considering the highly resource limited tokens, we propose a lightweight challenge response based mechanism re-using the MAC() function developed for Wisecr. The server sends a randomly generated challenge $c \leftarrow \text{RNG}()$ and evaluates the corresponding response $r'$ to validate the installation. We provision a new session key $sk$ to enable the remote attestation to proceed independent of the previous stages, whilst avoiding the derivation of a key on device to reduce the overhead of the attestation routine.

We propose two modes of attestation; a fast mode and an elaborate mode to trade-off veracity of the verification against computational and power costs. The fast mode only examines the token serial number ($\text{id}_i$) and the version number ($\text{ver}_i$). While the elaborate mode traverses over an entire memory segment. The elaborate mode is relatively more time consuming but allows the direct verification of the code installed on the target token $T_i$.

We illustrate in (Fig. 4) and demonstrate (in Section 4.5) the elaborate mode (more veracious and computationally intensive) where response $r' \leftarrow \text{MAC}_{sk}(c\|\text{selected segment (firmware)}\|\text{id}_i\|\text{ver}_i)$ attest the application memory segment containing the installed firmware. In contrast, the fast method computes the response as $r' \leftarrow \text{MAC}_{sk}(c\|\text{id}_i\|\text{ver}_i)$.

2.3 Token Security Requirements and Functional Blocks

Our design is intentionally minimal and requires the following security blocks.

Immutable Bootloader (Section 3.1) We require a static NVM sector $M_{tx}$ that is write-protected to store the executable bootloader image to ensure the bootloader can be trusted post deployment where, for example, firmware (application) code vulnerabilities or software bugs do not lead to the corruption of the bootloader and the integrity of the bootloader can be maintained.

Secure Storage (Section 3.1) To store a device specific secret, e.g., $k_i$, we require an NVM sector $M$ read-only accessible by the immutable bootloader in sector $M_{tx}$. This ensures the integrity and security of non-volatile secrets post deployment since the firmware (application) code cannot be trusted, for example, due to potential vulnerabilities or software bugs that can lead to the corruption of non-volatile memory contents.

Uninterruptible Bootloader Execution (Section 3.2) During the execution of the bootloader stored in sector $M_{tx}$, execution cannot be interrupted until the control flow is intentionally released by the bootloader.

Efficient Security Primitives (Section 3.3) The update scheme requires: i) a symmetric key primitive; and ii) a keyed hash primitive for the message authentication code that are both computationally and power efficient. In Section 2 we discuss how the associated functional blocks are engineered on typical RF-powered devices built with ultra-low power commodity MCUs.

3 On-device Security Function Engineering

To provide comprehensive evaluations and demonstrations, we selected the WISP5.1LRG CRFID device with an open-hardware and software implementation for our token $T$. This CRFID device uses the ultra-low power MCU MSP430FR5969 from Texas Instruments. Consequently, for a more concrete discussion, we will refer to the WISP5.1LRG CRFID and the MSP430FR5969 MCU in the following.

3.1 Immutable Bootloader & Secure Storage

For resource limited MCUs, several mechanisms—detailed in the Appendix A—exists for implementing secure storage: i) Isolated segments; ii) Volatile keys; iii) Execute only memory; and iv) Runtime access protections. We opt for achieving secure storage and bootloader immutability using Runtime Access Protection by exploiting the MCU’s memory
protection unit (MPU), which offers flexibility to the bootloader. In particular, the MPU allows read/write/execute permissions to be defined individually for memory segments at power-up—prior to any firmware (application) code execution. Wisecr requires the following segment permissions to be defined by the bootloader to prevent their subsequent modifications through application code by locking the MPU:

**Segment** \( M \) is used as the secure storage area. During application execution, any access (reading/writing) to this segment results in an access violation, causing the device to restart in the bootloader.

**Segment** \( M_{rx} \) contains the bootloader, device interrupt vector table (IVT), shared code (e.g., EPC Gen2 implementation). During application execution, writing to this segment results in an access violation.

**Segment** \( M_{rwx} \) covers the remaining memory, and is used for application IVT, code (firmware) and data.

### 3.2 Uninterruptible Bootloader Execution

The execution or control flow of the bootloader on the token must be uninterruptible by application code and power-loss events to meet our security objectives but dealing with brownout induced power-loss events is more challenging. Power loss leaves devices in vulnerable states for attackers to exploit; therefore, we focus on innovative, pragmatic and low-overhead power-loss prevention methods. Our approach deliberately mitigates the chances of power-loss. In case a rare power-loss still occurs, the token will discard all state—including security parameters such as the broadcast session key; subsequently, the Server will re-attempt to update the firmware by re-commencing a fresh update session with this token. We detail our solution below.

#### 3.2.1 Managing Application Layer Interruptions

The bootloader must be uninterruptible (by application code) for security considerations. For instance, the application code—due to an unintentional software bug or otherwise—could interrupt the bootloader while the device key is in a CPU register, so that the application code (exploited by an attacker) can copy the device key to a location under its control, or completely subvert access protections by overriding the MPU register before it is locked.

Recall, the memory segment \( M_{rx} \) (see Section 3.1) includes the memory region containing the IVT. This ensures that only the bootloader can modify the IVT. Since the IVT is under the bootloader’s control, we can ensure that any non-maskable interrupt is unable to be directly configured by the application code, whereas all other interrupts are disabled during bootloader execution. Consequently, the interrupt configuration cannot be mutated by application code.

#### 3.2.2 Managing Power-Loss Interruptions

Frequent and inevitable power loss during the bootloader execution will not only interrupt the execution, degrading code dissemination performance but also compromise security. Although intermittent computing techniques relying on saving and retrieving state at check-points from NVM—such as Flash or EPPROM—is possible, these methods impose additional energy consumption and introduce security vulnerabilities revealed recently [22].

Confronted with the complexity of designing and implementing an end-to-end scheme under extreme resource limitations, we propose an on-device Power Aware execution Model (PAM) to: i) avoid the overhead of intermittent computing techniques; and ii) enhance security without saving check-points to insecure NVM.

We observe that only a limited number of clock cycles are available for computations per charge and discharge cycle (Intermittent Power Cycle or IPC) of a power harvester, as illustrated via comprehensive measurements in Fig. 2. Further, the rate of energy consumption/depletion is faster than energy harvesting. We recognize that there are three main sources of power-loss: i) (CPU) energy required for function computation exceeding the energy supply capability from the harvester; ii) (FRAM.R/W) memory read/write access such as in executing Blockwrite commands; and iii) (RFID) power harvesting disruptions from communications—especially for backscattering data in response to EPC Gen2 commands.

To understand the severity of these four causes, we measure the maximum time duration before brownout/pow loss versus the harvested power level for each task—CPU, FRAM.R, FRAM.W and RFID. In the absence of a controlled RF environment (i.e., anechoic chamber), it is extremely difficult to maintain the same multipath reflection pattern. Especially when changing the distance between the radiator reader antenna and an instrumented CRFID device considering the multipath interference created by the probes, cables, and the nearby oscilloscope and researcher to monitor the device’s internal state. To minimize the difficulty of conducting the experiments, we place the CRFID device at a fixed distance (20 cm) whilst keeping all of the equipment at fixed positions, and adjust the transmit power of the RFID reader through the software interface. According to the free-space path loss equation [36], adjusting the transmit power of the RFID reader or changing the distance can be used to vary the available power at the CRFID device. We describe the detailed experimental settings in Appendix [7].

For experiments without the requirement for monitoring the device’s internal state, we still employ distance-based measurements as in previous studies [7], [17], [21].

The results are detailed in Fig. 5. For a transmit power greater than 800 mW, the CRFID transponder continuously operates without power failure within 100 seconds. If the reader transmit power is below 800 mW, the average operating time of the RFID task drops as the power level decreases. This is because the RFID communication process invokes
shorting the antenna, during which the energy harvesting is interrupted. Notably, different from Flash memory, reading data from FRAM (FRAM.R) consumes more power than writing to it (FRAM.W) as a consequence of the destructive read and the compulsory write-back [37]. Consequently, we developed:

- The Pilot-Observable Mode to reduce the occurrence of RFID tasks by enabling observing devices to listen to broadcast packets in silence whilst electing a single Pilot token to respond to the Server.
- The Power Aware Execution Model (PAM) to ensure memory access (FRAM tasks) and intensive computational blocks of the security protocol (CPU tasks) do not exceed the powering capability of the device.

Our PAM model builds upon [17], [38] in that, these are designed for execution scheduling to prevent power-loss from brownouts. Compared to [17], we consider dynamic scheduling of tasks and in contrast to [38] sampling of the harvester voltage (only possible in specific devices) within the application code, we consider dynamic scheduling determined by the more resourceful Server $S$ using a single voltage measurement reported by a token $T$ (see Appendix C for detailed comparison). We outline the means of achieving our PAM model on a token below.

During the Security Association stage shown in Fig. 3, a token measures and reports the voltage $V_{t} \leftarrow S\text{MIFS}(t)$ to the Server. The $V_{t}$ measurement indicates energy that can be harvested by token $T_{i}$ under the settings of the current firmware update session. According to $V_{t}$, the Server determines the active time period $t_{\text{active}}$ and LPM time period $t_{\text{LPM}}$ for each CRFID device (detailed development of a model to estimate $t_{\text{active}}$ and $t_{\text{LPM}}$ from $V_{t}$ is in Appendix D). Consequently, each CRFID device’s execution model is configured by the Server with device specific LPM and active periods at run-time. Hence, an adaptive execution model customized to the available power that could be harvested by each CRFID device is realized. Notably, this execution scheduling task is outsourced to the resourceful Server.

In this context, we assume the distances between the antenna and target CRFID devices are relatively constant during the short duration of a firmware update. Firmware updates are generally a maintenance activity where CRFID integrated components are less likely to be mobile to ease maintenance, such as during the scheduled maintenance of an automated production line [39], night time updates in smart buildings when people are less likely to be present and facilities are inoperative [40], or the pre-flight maintenance or inspection of aircraft parts while parked on an apron [9]. Further, it is desirable to maintain a stable powering channel in practice by ensuring a consistent distance during the maintenance or patching of devices for a short period. This is a more reasonable proposition than the wired programming of each device. Hence, the relatively fixed distance is a reasonable assumption in practice. Notably, given the challenging nature of the problem, previous non-secure firmware update methods, such as $R^{1}$ [21] and Stork [7], were evaluated under the same assumption.
when the success rate results without PAM—using the continuous execution model (CEM)—is compared with those of PAM at decreasing operating power levels. However, as expected, we can also observe that the dynamically adjusted execution model parameters ($t_{LPM}$ and $t_{active}$) of PAM at decreasing power levels to prevent power loss events and increase latency or the time to complete the routine. When PAM is compared with IEM, the dynamically adjusted execution model parameters allow PAM to demonstrate an improved capability to manage interruptions from power-loss at poor powering conditions; this is demonstrated by the higher success rates when the reader transmits power is at 188 mW and 178 mW. Since IEM encodes operating settings programmatically during the device provisioning phase [17], we can observe increased latency at better powering conditions when compared to PAM which allows a completion time similar to that obtained from CEM when power is ample. Thus, PAM provides a suitable compromise between latency and successful completion of a task at different powering conditions.

Notably, the RFID media access control (MAC) layer on a CRFID device is implemented in software as assembly code and executed at specific clock speeds to ensure strict signal timing requirements in the EPC Gen2 air interface protocol. Additionally, protocol message timing requirements place strict limits on waiting periods for device responses. Hence, we do not consider the direct control of the execution mode during communication sessions for managing power consumption and instead rely on the Pilot-Observer mode method we investigate next.

**TABLE 2. Execution overhead of pilot and observer tokens when receiving broadcast packets.**

| Clock Cycles | Memory Usage (Bytes) | Operation |
|--------------|----------------------|-----------|
| Pilot tokens receiving | 23,082 | 12 | 2 | apply decoding, prepare reply (e.g., compute CRC) |
| Pilot tokens replying | 1,131 | 0 | 0 | communication (backscattering) |
| Observer tokens receiving | 22,002 | 12 | 2 | apply decoding |

| Numbers are collected using a JTAG debugger where the reported values are averages over 100 repeated measurements. We provide a detailed discussion of the experiments and analysis process in Appendix C. |

**Pilot-Observer Mode.** We observed and also confirmed in Fig. 5 that the task of responding to communication commands will likely cause power loss. During the Secure Broadcast stage shown in Fig. 4, communication is dominated by repeated SecureComm commands with payloads of encrypted firmware and the data flow is uni-directional. Intuitively, we can disable responses from all the tokens to save energy. However, the SecureComm command under EPC Gen2 requires a reply (ACK) from the token to serve as an acknowledgment. An absent ACK within 20 ms will cause a protocol timeout and execution failure.

To address the issue, we propose the pilot-observer mode inspired by the method in Stork [7]. A critical and distinguishing feature of our approach is the intelligent election of a pilot token from all tokens to be updated—we defer to Appendix F for a more detailed discussion on the differences. As illustrated in Fig. 8(a), our approach places all in-field tokens to be updated into an observer mode except one token elected by the Server to drive the EPC Gen2 protocol—this device is termed the Pilot token. By doing so, observer tokens process all commands such as SecureComm—ignoring the handle designating the target device for the command—whilst remaining silent or muting replies to all commands whilst in the observer mode. Muting replies significantly reduce energy consumption and disruption to power harvesting of the tokens.

We propose electing the token with the lowest reported Vt as the pilot based on the observation: measuring powering channel state from the token, obtained from $V_{t_i} \leftarrow$ SNIFF$(t)$, is the most reliable measure of power available to a given device (see the discussion in Appendix D).

We recognize that it is very difficult to implement an explicit synchronization method to ensure the observer tokens stay synchronized with the pilot token in the secure broadcast update session. This is due to the level of complexity and overhead that an explicit method would bring and the consequence of such an overhead would be the increased occurrence of failures of a secure broadcast update session due to the additional task demands on tokens—we discuss the problem further in section 6. Although synchronization between the pilot and observer tokens are not explicit, the Pilot-Observer method implicitly enforces a degree of synchronicity. The selected pilot token—tasked with responding to the Host commands during the broadcast—has to spend more time than observer tokens to prepare the uplink packet and send a reply (ACK) to the Host (RFID reader) to meet the EPC Gen2 specification requirements as summarized in Table 2, hence the update process is controlled by the slowest token. Further, since we elect the token with the lowest powering condition as the pilot, the update is controlled by the most energy-starved token. This strategy leads to other tokens having higher levels of available power and extra time to successfully process...
the broadcasted firmware and remain synchronized with the update process. Hence, if the pilot succeeds, observers are expected to succeed.

Validation of Pilot Election Method. To demonstrate the effectiveness of our pilot token election method, we considered seven different pilot token selection methods based on token based estimations of available power and indirect methods of estimating the power available to a token by the server: 1) Lowest \( V_t \): this implies the pilot is selected based on the most conservative energy availability at token; 2) Highest \( V_t \): the pilot has to reply to commands, hence we may expect higher power availability to prevent the failure of a broadcast session due to brownout at the pilot; 3) Lowest Read Rate: a slow pilot allows observers to gather more energy during the broadcast and remain synchronized with the protocol to prevent failure of the observer tokens; 4) Highest Read Rate: a faster pilot could reduce latency; 5) Lowest Received Signal Strength Indicator (RSSI): successful communication over the poorest channel may ensure all observers are on a better channel (RSSI acts as an indirect measure of the powering channel at a token); 6) Highest RSSI: prevent pilot failure due to a potentially poor powering channel at the pilot token; and 7) Random selection: monkey beats man on stock picks.

We have extensively evaluated and compared all of the above seven pilot token selection methods. The experiment is conducted by placing 4 CRFID tokens at 20 cm, 30 cm, 40 cm and 50 cm above an reader antenna; each CRFID is placed in alignment with the four edges of the antenna (See Fig. 12(d)). We repeated the code dissemination process 100 times at each distance test, for each of the 7 different pilot selection methods. We recorded two measures: i) latency (seconds); and ii) number of times the broadcast attempt updated all of the 4 in-field devices. As illustrated in Fig. 8(b), at 40 cm where the power conditions are more critical at a token, the selected pilot token with the lowest token voltage (\( V_t \)) shows an enormous advantage, in terms of both latency and attempt number. Overall, our proposed approach (electing the lowest \( V_t \)) ensures that most observer tokens are able to correctly obtain and validate the firmware in a given broadcast session on the first attempt in the critical powering regions of operation (we provide a theoretical justification in Appendix D).

We also evaluated the reduction in power consumption achieved from computational tasks, in addition to eliminating the communication task. While we provide a detailed discussion of the experiments and analysis process in Appendix C, we summarize our experimental results in Table 2. The measurements show that the observer tokens, compared to the pilot token, consumes 2,211 less clock cycles per firmware packet from the Host. This is a reduction of 9.13% to process each firmware packet sent from the Host.

Summary. Our pilot-election based method effectively reduces the chance of power failure as well as de-synchronization of the observer tokens during a firmware broadcast session. Our approach is able to ensure that more of the observer tokens are able to correctly obtain and validate the firmware during a single broadcast sessions.

3.3 Efficient Security Primitives

Wisecr requires two cryptographic primitives: i) symmetric key primitive \( SKP() \); and ii) a keyed hash primitive for the message authentication code \( MAC() \). When selecting corresponding primitives in the following, two key factors are necessary to consider:

1) Computational cost: The CPU clock cycles required for a primitives quantifies both the computation cost and energy consumption. Therefore, clock cycles required for executing the primitives need to be within energy and computational limits of the energy harvesting device.

2) Memory needs: On-chip memory is limited—only 2 KiB of SRAM on the target MCU—and must be shared with: i) the RFID protocol implementation; and ii) user code.

Symmetric Key Primitives. We first compare block ciphers via software implementation benchmarks—clock cycle counts and memory usage—on our target microcontroller [41], [42]. We also considered the increasingly available cryptographic co-processors in microcontrollers: our targeted device uses an MSP430FR5969 microcontroller and embeds an on-chip hardware Advanced Encryption Standard (AES) accelerator (we refer to as HW-AES) [43]. Based on the above selection considerations, HW-AES is confirmed to outperform others. Specifically, HW-AES to encrypt/decrypt a 128-bit block consumes 167/214 clock cycles with a power overhead of 21 \( \mu A/MHz \); therefore we opted for HW-AES for SKP.Dec function implementation on our target device. We configured AES to employ the Cipher-Block Chaining (CBC) mode. Similar hardware AES resources can be found in a variety of microcontrollers, ASIC, FPGA IP core and smart cards. In the absence of HW-AES, a software AES implementation, such as tiny-AES-c can be an alternative.

Message Authentication Code. MACs built upon BLAKE2s-256, BLAKE2s-128, HWAES-GMAC and HWAES-CMAC on our targeted MSP430FR5969 MCU were taken into consideration [17]. We selected the 128-bit \( HWAES-CMAC—Cipher-based Message Authentication Code \)—based on AES since it yielded the lowest clock cycles per Byte by exploiting the MCU’s AES accelerator (HW-AES).

3.4 Bootloader Control Flow

We can now realize an uninterruptible control flow for an immutable bootloader built upon on the security properties identified and engineered to achieve our Wisecr scheme described in Section 2.2. We describe the bootloader control flow in Fig. 9.

At power-up, 1) the token performs MCU initialization routines, 2) setup MPU protections for bootloader execution and carries out a self-test to determine whether a firmware update is required, or if there is a valid application installed. If no update is required and the user application is valid, 3) the bootloader configures MPU protections for application execution, before handing over control to the

1. We are aware of CBC padding oracle attacks; however, in our implementa-tion, the response an attacker can obtains is to the CMAC failure or success and not the success or failure of the decryption routine. Alternatively, the routines can be changed to employ authenticated encryption in the future, with an increase in overhead.

2. The implementation in NIST Special Publication 800-38B, Recommendation for Block Cipher Modes of Operation: the CMAC Made for Authentication is used here.
application. During the application execution, (4) the user code is executed, (5) then the token T waits for command from the Server S, the Server S may send an Inventory commands to instruct the token T to (6) send back e.g., sensed data, or in (7) setup the WisecrMode flag and trigger a software reset in preparation for an update.

Security Association. Upon a software reset, a set WisecrMode flag directs the token T to enter the Security Association stage. (8) Subsequently, the token waits for further instructions from the Server. On reception of an Authenticate command, carrying an encrypted broadcast session key \( \langle sk \rangle_i \) and the MAC tag \( s_i \) of the new firmware, (9) the token T decrypts \( \langle sk \rangle_i \) with its device key \( k \), and acquires the session key \( sk \).

Secure Broadcast. Recall, at this stage, all tokens selected for update will be switched into the observer mode except the pilot token that is set to respond to the Server. The pilot token in state (10) receives a new chunk of encrypted firmware \( \langle \text{firmware} \rangle^{(3)} \), and (11) stores it into the specified memory location. (12) The pilot token sends reply to the Server. In (13), for tokens in observer mode, they silently listen to the communication traffic between the Server and the Pilot token without replying. In other words, tokens under observer mode receives the encrypted firmware chunks, (14) store chunks in memory but ignores unicast handle identifying the target device; this significantly saves observers’ energy from replying as detailed in Section 3.2.2 Once an End of Broadcast (EOB) message is received, all tokens stop waiting for new packets and start firmware decryption (15).

Validation. The token computes a local MAC tag \( s'_i \), including the decrypted firmware, and compares it with the received MAC tag \( s_i \). (16) The firmware is accepted, applied to update (17) the token, if \( s'_i \) and \( s_i \) are matched, and (19) the WisecrMode flag is reset; otherwise, (18) the firmware is discarded and the update is aborted. Subsequently, each token performs a software reset to execute the new firmware or reinitialize in bootloader mode if the firmware update is unsuccessful.

Remote Attestation. On reception of an Authenticate command with an instruction to perform remote attestation, (20) the token first decrypts the session key \( sk \) and reads (21) \( id_i \), \( ver \), and \( \text{firmware} \) from the NVM according to the specified memory address and size (firmware is only used in the elaborate mode, in the fast mode only \( id_i \) and \( ver \) are involved). The attestation response is then computed as \( r \leftarrow MAC_{sk}(c\|\text{selected segment (firmware)}\|id_i\|ver_i) \) if the elaborate mode is selected (22) or \( r \leftarrow MAC_{sk}(c\|id_i\|ver_i) \) if using the fast mode (24). Subsequently, the response \( r \) is sent back to the Server S, (25) the WisecrMode flag is cleared and (19) the device is reset.

Notably, a power-loss event during the control flow will result in a reset and rebooting of the token T and a transition out from the firmware update state. Most significantly, in such an occurrence, the immutable bootloader functionality is preserved. Although the loss of state implies that a Server S must reattempt the secure update, we prevent the token from being left in a vulnerable state to inherently mitigate security threats posed in the power off state (22).

4 END-TO-END IMPLEMENTATION AND EXPERIMENTS

This section elaborates on software tools, the end-to-end implementation of Wiserc and extensive experiments conducted to systematically evaluate the performance of Wiserc.

4.1 End-to-End Implementation

We implement a bootloader and a Server Toolkit to wirelessly and simultaneously update multiple CRFID transponders using commodity networked RFID hardware and standard protocols. We realize the Wiserc scheme in Fig. 4 and the identified security property requirements. Specifically, we employ MSP430FR5969 MCU based WIPS5.1LRG CRFID devices. The MSP430FR5969 microcontroller has a 2 Kib SRAM and a 64 Kib FRAM internal memory. The implementation is a significant undertaking and includes software development for the CRFID as well as the RFID reader and backend services for the server update mechanisms. Given that we have open sourced the project, we describe: i) the bootloader in Section 4.2 and ii) the Sever Toolkit and the protocols for Host-to-RFID-reader and Reader-to-CRFID-device communications for implementing Wiserc over EPC Gen2 in Appendix B.
4.2 Bootloader and Memory Management

**Wisecr Bootloader.** The immutable bootloader supervises firmware execution while needing to be compatible with standard protocols, we developed our bootloader based on the Texas Instrument’s recent framework for wireless firmware updates—MSP430FRBoot [44] and the code base from recent work [17] employing the framework. Such construction ensures a standard tool chain for compilation and update of new firmware whilst the usage of industry standards is likely to increase adoption in the future. We compile the firmware code into ELF (Executable and Linkable Format) made up of binary machine code and linker map specifying the target memory allocation—the memory arrangement is illustrated Fig. 10.

**Wisecr Memory Management.** For implementing the Secure Storage component, several different mechanisms are available (as summarized in Appendix A). In Wisecr, we select to use the Runtime access protection (e.g. using MPU segments at run-time) In this scheme, secure storage is available on device boot-up, but is locked (until next boot-up) by the bootloader before any application code is executed. We employed this method and the implemented memory arrangement is described in Fig. 10 Switching to privilege mode is done by the bootloader on boot up, and the applications do not need to make any specific modifications. If an application attempts to access a privileged resource, e.g. overwriting the bootloader segment, a power-up clear (PUC) will be triggered by the MPU to cause reboot, before any risky operation.

Importantly, any power-on reset, regardless of the cause, will result in a reboot and the execution of the bootloader before transferring control to application code—see Application execution stage in Fig. 9 Prior to entering the application execution stage, the bootloader enforces the MPU policy for application execution (see 3). This step is necessary with the target MCU used in our implementation as it only allows defining three memory segments for protection. Thus, we are able to rely on the very limited protections provided by the MCU to achieve the security objectives of a trusted bootloader; recall, in our threat model, the bootloader is trusted, and we realize this in practice by ensuring that the bootloader provisioned is immutable where the secrets stored on device must remain inaccessible and immutable to the application firmware. Now, it is impossible to revoke the policy enforced during the application execution stage, unless the device is power-cycled. But, the device will enter the bootloader stage after a reboot and MPU protections will be re-enabled prior to executing any application code. We summarize the memory protections developed using the limited MPU configurations to realize Wisecr security requirements in bootloader and application execution modes in Section 3.2 therein, we also discuss alternative methods to realize such protections to ensure the generalization of Wisecr to other MCUs.

![Fig. 10](image_url)

**Remote Attestation.** As shown in Fig. 11(a) Remote Attestation routine is an integral part of the immutable bootloader, it has access to all memory segments: Token device key $k_i$, version number $ver_i$, tag serial number $id_i$ and the installed user application code firmware. A challenge $c$ is a one-time use random string that is generated by the Server $S$. The $r'$ is the report to be transferred back to the Server. On receiving an encrypted session key $\langle sk_i \rangle$, the Token decrypts it with SKPDec and obtains the session key $sk_i$. In the fast mode illustrated in Fig. 11(b), the response $r'$ is calculated based on $id_i$ and $ver_i$. In contrast, the response $r''$ is computed over an entire memory segment, such as the firmware, in the elaborate mode as depicted in Fig. 11(c).

4.3 **Wisecr Implementation Overheads**

We first evaluate the execution and implementation overhead of each Wisecr security functional block; results are summarized in Table 3. The execution overhead is measured in terms of clock cycles for installing a firmware of 240 Bytes. The implementation overhead is measured in memory usage, consisting of ROM for code and constants and RAM for run-time state. Secondly, we assess the necessary hardware modules such as hardware AES accelerator (HW-AES), analog-to-digital converter (ADC) and Timer. All functional blocks are implemented in platform independent C source files. We summarize the implementation costs for each stage; the most significant implementation and execution overhead is from the Validation stage because of the computationally heavy MAC() function—recall Remote Attestation is an optional stage.

In Table 3, we also compare with SecuCode™ presently, the only CRFID firmware update scheme considering security—notably, the scheme only prevents malicious code injection attacks and is designed to update a single device at a time as highlighted in the method comparison Table 4. In summary, Wisecr consumes 49.97% more clock cycles, 40.95% more ROM and 97.43% more RAM space than the SecuCode. However, Wisecr can update multiple...
We summarize our evaluations below.

**4.4 Experiment Designs and Evaluations**

We employed four WIPS5.1LRG CRFID devices and an Impinj R420 RFID reader with a 9 dBi gain antenna to communicate with and energize the CRFID devices. All of the experiments are conducted with the RFID reader feeding the antenna with 30 dBm output power. Given that, the insecure wireless channel and validates firmware installation. As expected, the performance improvements and additional security features are achieved at an increased implementation overhead.

**4.5 Performance Evaluation and Results**

We use two performance metrics: i) end-to-end latency; and ii) throughput (bits per second). Latency is the time elapsed from the Server Toolkit transmitting the firmware to an RFID reader using LLRP commands to the time the Server Toolkit confirms the acknowledgment of successfully updating *all chosen tokens*. Throughput is the total data transferred over the latency, where

\[
\text{Throughput (bps)} = \frac{(\text{firmware size}) \times \text{Num. of Tokens}}{\text{Latency}}
\]

Our evaluation is carried out under three different controlled variables: i) distance; ii) number of tokens; and iii) firmware size. In each experiment, only one variable is changed and our results are collected over 100 repeated measurements, with outliers outside of 1.5 times upper and lower quartiles removed.

First, we transfer the same firmware code (a 407 Byte accelerometer service) to four target devices located at distances from 20 cm to 40 cm, covering good to poor powering channel states, to evaluate the *stability* of the Wisecr scheme. As expected, we can observe in Fig. 12(a) that the performance of all three schemes degrades with increasing distance. Notably, Wisecr and SecuCode outperforms the Wisecr (Seq) because, Wisecr (Seq) incurs a larger overhead through the need for executing a Security Association setup to broadcast firmware parameters, for each device. Further, SecuCode (without IP protection) does not need to execute the power intensive firmware decryption operations, and thus is less likely to encounter power-loss and update session failure or require the extra time necessary by Wisecr to decrypt the firmware. As expected, Wisecr outperforms albeit the added security functions provided in comparison to SecuCode.

Second, following the method and metrics in Stork [7], we tested the performance of the schemes by increasing the number of CRFID devices to be updated. We can see in Fig. 12(b) that the latency of both Wisecr (Seq) and SecuCode increases linearly while Wisecr remains relatively steady regardless of the number of devices to update. Consequently, Wisecr exhibits significantly improved throughput as the number of device increases. Further, we examine performance under increasing firmware size: 115 Bytes; 407 Bytes (a sensor service code); and 1280 Bytes (a computation code firmware). Efficacy of broadcasting to multiple devices simultaneously is validated by latency and throughput performance detailed in Fig. 12(c).

Third, all three candidates show improved efficiency as larger firmware sizes are transmitted; Wisecr’s significantly
We also conducted an evaluation of the execution overhead (latency) introduced by the remote attestation routines. Since remote attestation is performed on one singulated token at an instance, we only examine its impact on one individual device. The latency can be aggregated for multiple devices. As illustrated in Fig. 12, the remote attestation in fast mode always completes in 1.1 ms, regardless of the firmware size. While the time required to complete the elaborate mode scales from 1.3 ms to 6.5 ms with respect to firmware sizes from 115 Bytes to 1280 Bytes.

Fig. 12. Comparing Wisecr, Wisecr(Seq)—Wisecr operating in sequential mode, SecuCode with no secure broadcast support under increasing: (a) Distance (4 Tokens with a 407 Byte firmware), (b) Number of Tokens (at 20 cm with 407 Byte firmware) and (c) Firmware size (at 20 cm with 4 Tokens). The experimental setup illustrated in (d) shows (1) a host PC, (2) a RFID reader, (3) a reader antenna and (4) four CRFID devices mounted on a foam frame, supported by a wooden tripod.

4.6 Case Study

As shown in Fig. 14, we employ four CRFID devices embedded in a 3D printed unmanned aerial vehicle (UAV) rotor prototype. The CRFID devices are factory programmed with firmware for monitoring the centrifugal load and the wired programming interface is disabled prior to embedding and deployment. All four CRFID devices are required to be updated wirelessly and securely with code for monitor the blade flapping vibration in a wind tunnel test.

We employed Wisecr to simultaneously, securely and wirelessly update the four CRFID sensor devices with the 391-Byte firmware code. The experimental results summarized in Fig. 14 show successful updates for 100 repeated attempts in two settings: i) when the rotor is attached to the UAV Wisecr updated all of the devices in the first attempt in 76% of the time with an average latency of 28.12 seconds; and ii) when the rotor assembly is free standing, Wisecr updated all of the devices in the first attempt in 89% of the time with an average latency of 14.27 seconds.

A demonstration of the secure firmware update process in using our end-to-end implementation illustrated in Fig. 14 is available at https://youtu.be/GgDHPJi3A5U. We open source the complete source code for Wisecr and related tools at https://github.com/AdelaideAuto-IDLab/Wisecr.

4.7 Security Analysis

Under the threat model in Section 2.1, we analyze Wisecr security against: i) IP theft (code reverse engineering); ii) malicious code injection attacks under code alteration, loading unauthorized code, loading code onto an unauthorized device, and code downgrading; and iii) incomplete code installation.

IP Theft or Code Reverse Engineering. The wirelessly broadcasted firmware is encrypted using a one-time 128-bit broadcast session key sk. Without the knowledge of the broadcast session key, the adversary A is unable to obtain the plaintext firmware through passive eavesdropping. Once the firmware is decrypted on the token, the binaries cannot be accessed outside the immutable bootloader. Therefore, the probability of a successful IP theft is now determined by the security provided by the size of the selected keys—we employ 128-bit keys in the Wisecr implementation.

8. Although previous studies have performed experiments with static tags, we also attempted to update the tokens while the rotor blades are mobile by rotating them at approximately 1 RPM. We were able to update tokens over 50% of the time. As expected, the changing powering conditions dramatically reduced the update rate (see details in Appendix 1).
Loading Unauthorized Code. The security property of a MAC tag $s_i \leftarrow \text{MAC}_{k_i}(\text{firmware}||\text{ver}_i||\text{nver})$ ensures that the adversary $A$ cannot commit a malicious firmware injection attack without the knowledge of the session key $sk$ — recall that the sharing of $sk$ is protected through a secure channel established with a token specific private key $k_i$. Hence, only the Server with the session key $sk$ is able to produce a valid MAC tag to a token $T$. Hence, the probability of launching a successful attack by the adversary $A$ is limited to the probability of successfully obtaining the device key $k_i$, and/or the session key $sk$ in a man-in-the-middle attack to successfully construct a MAC tag and disseminate a malicious firmware that will be correctly validated by the target tokens. Therefore, without knowledge of $k_i$ or $sk$, the probability of fooling a token $T$ to inject a malicious firmware by $A$ is no more than the brute-force attack probability $2^{-128}$ determined by the key size $|k_i| = 128$.

**Code Alteration.** For each firmware update, a MAC tag $s_i \leftarrow \text{MAC}_{k_i}(\text{firmware}||\text{ver}_i||\text{nver})$ is used to verify code integrity. Therefore, without knowledge of the session key $sk$, the adversary $A$ can not generate a valid MAC tag for an altered firmware. Any attempted changes to the firmware during the code dissemination will be detected and, thus, firmware discarded by the token.

**Loading Code onto an Unauthorized Device.** Each authorized device $i$ maintains a unique and secret device specific key $k_i$ only known to the Server $S$. Therefore, an unauthorized device cannot decrypt the session key $sk_i$ to install a recorded firmware encrypted with $sk_i$ of an authorized device.

**Code Downgrading.** The adversary $A$ can attempt to downgrade the firmware to an older version to facilitate exploitation of potential vulnerabilities in a previous distribution. This can be attempted through a replay attack by impersonating the Server. However, for each firmware update, a specific MAC tag: $s_i \leftarrow \text{MAC}_{k_i}(\text{firmware}||\text{ver}_i||\text{nver})$ is generated based on two monotonically increasing version numbers: \text{ver}, and \text{nver}. Without direct access to modify the Secure storage contents in region $M$ to re-write the current version number of a device to an older version, the attacker cannot replay a recorded MAC tag from a previous session to force a token to accept an older firmware. By virtue of the monotonically increasing version numbers, and the secure MAC primitive protected by the session key $sk$, a successful software downgrade using a replay attack cannot be mounted by the adversary $A$.

**Incomplete Firmware Installation.** In a man-in-the-middle attack, the adversary $A$ may attempt to prevent a new firmware installation and spoof a device response with an updated version number during an interrogation—the version number is public information and sent in plaintext as shown in Fig. 4. Hence, a token may be left executing an older firmware version with potential firmware vulnerabilities. The Server can verify that a specific disseminated firmware deployed by the token is the same as the one issued by the Server by performing a remote attestation. In our Wisecr scheme, we have considered an optional remote attestation stage (detailed in Section 2.2) to allow the Server to verify the firmware installation on a given token. In general, both code installation and attestation are bounded to the device key $k_i$, thus, it is infeasible to fool the Server without knowledge of the device key.

**Related-key Differential Cryptanalysis Attack.** In our security association stage, the session key $sk$ is encrypted multiple times with different device keys $k_i$. A related-key differential cryptanalysis of round-reduced AES-128 is demonstrated in [46]. The prerequisite to mount such an attack is that the attacker knows or is able to choose a relation between several secret keys and gain access to both plaintext and ciphertext [47]. In our approach, as mentioned in Section 2.1, $k_i$ chosen by the server are i.i.d., and only the ciphertext is publicly available where the attacker is not able to force the server to encrypt a plaintext of their choosing. Therefore related-key attacks cannot be mounted under our threat model. Even if such an attack is possible, to the best of our knowledge, there is no successful full-round related-key differential cryptanalysis attack against AES-128, which serve as the SKP function in our implementation.

5 Related Work and Discussion

Here, we discuss related works in the area of wireless code dissemination to CRFID devices. Notably, the topic of wireless code updating has been extensively studied for battery powered Wireless Sensor Network (WSN) nodes. For example, a recent study by Florian et al. [29] proposed updating the firmware and peer-to-peer attestation of multiple mesh networked IoT devices. Physical unclonable functions [17] and blockchains [48] have also been utilized in code dissemination.

But, such schemes [29], [48] are designed for battery powered WSN nodes featuring device-to-device communication capability, and supervisory control of operating systems (e.g. TinyOS), absent in batteryless CRFID devices (see challenges in Section 1). Further, batteryless devices operate under extreme energy and computational capability limitations. In particular, harvested energy is intermittent and limited and thus devices face difficulties supporting security functions such as key exchange using Elliptic Curve Diffie-Hellman used in [29]. Therefore, we focus on research into wireless dissemination schemes for CRFID like devices in our discussions. Further, we also discuss and compare our work with existing wireless methods developed for CRFID to highlight the aim of our scheme to fulfill unmet security objectives for simultaneous wireless firmware update to multiple CRFIDs.

**Wireless Code Dissemination to CRFID.** Given the recent emergence of the technology, there exists only a few studies on code dissemination to CRFID devices. Wisent from Tan et al. [18], and $R^3$ from Wu et al. [21] demonstrate a wireless firmware update method for CRFID. Subsequently, Aanjes et al. [7] proposed Stork, a fast multi-CRFID wireless firmware transfer protocol. Stork forces devices to ignore the RN16 handle in down-link packets—a form of promiscuous listening—to realize a logical broadcast channel in the absence of EPC Gen2 support for a broadcast capability; RN16 specifies the designated packet receiver. This technique enables Stork to simultaneously program multiple CRFIDs to achieve fast firmware dissemination. Our Pilot-Observer mode (Section 3.2.2) is based on a similar concept, but instead of always selecting the first seen device, as in Stork, we strategically elect the token with the lowest $V_i$ as the Pilot to achieve higher broadcast success. Brown and Pier
Remote Attestation. Attestation enables the Server to establish trust with the token’s hardware and software configuration. Existing mainstay remote attestation methods are unsuitable for a practicable realization in the context of intermittently powered energy harvesting platforms we focus on. For example, peer-to-peer attestation adopted in [29] is impractical in the CRFID context due to the lack of a device-to-device communication channel. In boot attestation [50], a public-key based scheme is proposed to fit ownership and third-party attestation, however public-key schemes are too computationally intensive for the batteryless devices we consider. Recently, a publish/subscribe mechanism based asynchronous attestation for large scale WSN is presented in SARA [51], however, such a publish/subscribe paradigm is yet to be supported over a standard EPC Gen2 protocol. In contrast, our lightweight-remote-attestation mechanisms (see Section 2.2) are inspired from the recent study in [19], where methods are designed for resource limited platforms and require no additional building blocks besides those necessary for Wisecr.

| TABLE 4. Comparison with Related Studies. |

Comparisons. Table 4 summarizes a comparison of Wisecr with wireless code dissemination studies specific to passive CRFID devices. Wisecr is the only secure scheme (prevent IP theft and malicious code injection, and provide attestation of firmware installation) for simultaneous update of passively powered devices. We have also extensively compared the performance of Wisecr with the non-secure code update method of Stork to provide an appreciation for the security overhead in an end-to-end implementation below.

5.1 Comparison with Stork (Insecure Method)

We extensively compared the performance of our secure Wisecr scheme with Stork [7]. Both methods aim to offer multiple CRFID wireless firmware updates, but security objectives are not considered by Stork. Comparisons are carried out under three different test settings:

- Four different operating ranges from 20 to 50 cm.
- Updating 1 to 4 tags concurrently in-field to evaluate reduced latency to update (or improvements to scalability) (as in Stork, tags are at 20 cm from the antenna).
- Consider three different firmware sizes (as in Stork, tags are at 20 cm from the antenna).

We measured two performance metrics: i) latency; and ii) throughput as defined in Section 4.5 for each test setting. For both Stork and Wisecr, we used the same binary files generated from the same compilation. The settings in the Wisecr Server Toolkit are: 10 attempts per broadcast run; lowest voltage \( V_{t1} \) pilot token selection method; Send Mode is set to Broadcast. Meanwhile, the settings in Stork are: BWPayload is set to throttle; Update Only is set to True; Reprogramming Mode is set to Broadcast; Compression is Disabled (as compression simply reduces the size of the firmware, we did not enable this option). Results are mean values from 100 repeated protocol update runs. Comparison results from our experiments are detailed in Fig. 15.

- From Fig. 15 (a): when powering channel state is reasonable i.e. from 20 cm to 40 cm, Wisecr outperforms Stork, as Wisecr does not need per-block checking and relies on the pilot token selection method to improve broadcast performance. However, Stork performs better than Wisecr at 50 cm when the powering channel condition is very poor because Stork is able to continue to transmit the firmware across power failures since the stork scheme does not need to meet any security requirements and therefore is able to send firmware payload in plaintext from the last correctly received payload. In contrast Wisecr gracefully fails when a power interruption cannot be prevented and all states (such as the session key) are lost and a new broadcast attempt must be made by the Server Toolkit.
- From Fig. 15 (b): Wisecr exhibits significantly better latency and throughput as the number of tokens increases.
- From Fig. 15 (c): both protocols show improved efficiency as larger payload/firmware sizes are transmitted. Notably, Wisecr exhibits much better efficiency attributed to the significantly reduced latency experienced during the broadcast method.

The gains in performance and faster updates to many devices achieved by Wisecr can be attributed to: i) our pilot token selection method to drive the protocol where

From Texas Instrument (TI) developed MSPBoot [49] in late 2016. They demonstrate an update using a UART or SPI bus to interconnect a MSP430 16-bit RISC microcontroller and a CC1101 sub-1GHz RF transceiver. However, none of the schemes, Wisent, R3, Stork and the work in [49], considers security when wirelessly updating firmware. SecuCode [17] took the first step to prevent malicious code injection attacks where a single CRFID device is updated. But SecuCode lacks scalability and performs device by device updates, cannot protect the firmware IP, and provides no validation of firmware installation.
6 Conclusion and Future Work

Our study proposed and implemented the first secure and simultaneous wireless firmware update to many RF-powered devices with remote attestation of code installation. We explored highly limited resources and innovated to resolve security engineering challenges to implement Wisecr. The scheme prevents malicious code injection, IP theft, and incomplete code installation threats whilst being compliant with standard hardware and protocols. Wisecr performance and comparisons with state-of-the-art through an extensive experiment regime have validated the efficacy and practicality of the design, whilst the end-to-end implementation source code is released to facilitate further improvements by practitioners and the academic community.

Limitations and Future Work: Our study is not without limitations. Although the Wisecr reasonably assumes (as in $R^3$ [21] and Stork [7]) that the devices are at relatively constant distances from an RFID reader antenna during the short duration firmware update process (approximately 16 s in the application demonstration), occasionally this assumption may not hold. For example, when re-programming devices on a conveyor belt, it is desirable to not delay the movement of the tags and to re-program whilst distances are changing. Development of a solution to the problem in the context of resource limited devices operating over a highly constrained air interface protocol is a challenging problem and an interesting direction for future work.

Additionally, every BlockWrite command used to broadcast the firmware contains a CRC-16 field for error detection [35]. In our Pilot-Observer mode, only the pilot-detected CRC errors are indicated to the Host; future work could consider the problem of broadcast reliability further. Notably, developing a method is non-trivial given the limitations of the EPC Gen2 air interface protocol.

In our secure update method, the pilot token and observer tokens do not explicitly synchronize progress due to the constrained air interface protocol not supporting token-to-token communications as well as the extremely limited available power. This also makes it difficult for the server to immediately, i.e. during the Secure Broadcast stage, to detect an observer token that has de-synchronized. Any synchronization would need to involve the Host performing this function, such as reading back of memory contents from a token’s download region and re-transmitting missing packets, at set intervals [2]. Hence, developing an explicit synchronization method in the context of a secure broadcast method forms an interesting direction for future work.

Further, it will be interesting to consider alternative mechanisms for validating the installation of firmware, such as the exploitation of the reply signal to the final packet delivering firmware to tokens. We leave this interesting direction to explore for future work.

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APPENDIX A
MEMORY MANAGEMENT COMPARISON

For implementing the Secure Storage component, several different mechanisms can be used:

1) Isolated segments (e.g. using IP encapsulation hardware). Requirements and limitations: It requires hardware features (such as IP encapsulation) to implement.

2) Volatile secret keys (see, for example, SRAM PUF [52]). Requirements and limitations: It might be computationally expensive to derive and erase the secret key, need a mechanism to ‘restore’ the volatile area on device restart, and a different mechanism is required to ensure that the bootloader is immutable.

3) Execute only memory (e.g. using MPU segments at compile time) In this scheme secure memory is encoded as instructions (e.g. MOV) in execute only memory (XOM) (see [29]). Requirements and limitations: Implementation can be complex, since any code in this region must ensure that it does not leak data (e.g. in CPU registers or volatile memory), including from arbitrary jumps into the code. Additionally, since the bootloader is also unable to write to this region, it cannot be used to protect dynamic secrets (e.g. the broadcast session key).

4) Runtime access protection (e.g. using MPU segments at runtime) In this scheme, secure storage is available on device boot-up, but is locked (until next boot-up) by the bootloader before any application code is executed. We selected this method in Wisecr. Requirements and limitations: Method requires MPU hardware with runtime configuration and locking, and the implementation must ensure that the MPU is always configured correctly before any application code is executed.

APPENDIX B
DETAILED WISECR UPDATE SCHEME

Server Toolkit. Our Server Toolkit can be executed on a host with network connectivity to an RFID reader. The App loads in the ELF file generated from the compilation process, parses and slices it into MSPBoot specified 128-bit-long commands suitable for the RFID reader. The App then uses LLRP commands to construct AccessSpecs and ROSpecs. These encode EPC C1Gen2 protocol commands such as BlockWrite and SecureComm commands to discover, engage and configure a networked RFID reader to execute the Wisecr protocol. Notably, we follow the same protocols for Host-to-RFID-reader and Reader-to-CRFID-device communications as in [7, 17] and detail implementation of Wisecr over EPC Gen2 in the Fig. 3

Wisecr Update Scheme Over EPC Gen2. As described in Fig. 4 Wisecr enables the ability to distribute and update firmware of multiple CRFID tokens, simultaneously. Given that a Server S communicates with an RFID device using EPC Gen2, a practicable, scalable and secure code dissemination scheme must be implemented over EPC Gen2. This requires communication between three separate entities: i) the host machine; ii) the reader; and iii) CRFID transponders—see main text Fig. 3. Our scheme description here focuses on the communication between CRFID devices—tokens T—and the RFID reader—the Server S over the EPC Gen2 protocol as illustrated in Fig. 16, our open source code base provides a complete description (https://github.com/AdelaideAuto-IDLab/Wisecr).

Authenticating the Acknowledgment in the Validation Stage. It is theoretically possible to compute and include a MAC tag in an acknowledgment message at the end of the Validation stage but the implementation of this in practice...
is not possible. Our current acknowledgment signal is based on exploiting the last message in a singulation session—see RFID singulation phase in the Validation stage in Fig. 16. This last message returns the the unique device identifier or EPC (electronic product code). We piggy back the current version number or EPC (electronic product code). We piggy back the current version number in the data field part of this message as our soft validation signal. This is possible because at power-up (whether it be software or hardware reset) the device executes the bootloader and during its execution copies the id, and version in the global SRAM memory region for use after the MPU (memory protection unit) prevents access to this content stored in the secure storage area (see memory protection unit segmentation diagram in Fig. 10). Notably, even if a MAC tag was computed by the bootloader after power cycling (reboot) in the Validation stage, and stored in global memory for access after MPU protections to be used during the singulation phase that follows, the data field in the last EPC message is limited to 96 bits. Thus, there is inadequate room to piggyback a 128-bit MAC tag. Further, this would be an added overhead since the MAC computation would need to occur each time a CRFID device is powered (booted), irrespective of whether the MAC is needed or not.

Thus, it is better to compute a MAC tag after reboot, on demand and when necessary by: i) singulating a token first; ii) instructing the token to compute the MAC tag; and iii) requesting the MAC tag. This is essentially the method we employ in the Remote Attestation stage that follows the Validation stage.

APPENDIX C

LOW OVERHEAD EXECUTION SCHEDULING

Buettnet, et al. proposed Dewdrop execution model to prevent a brownout event under unreliable powering by executing tasks only when they are likely to succeed by monitoring the available harvested power. Dewdrop explores a dynamic on-device task scheduling method, however, requires the overhead of collecting samples of the harvester voltage and task scheduling by the device’s application code.

In addition, Dewdrop is only suitable for CRFID devices equipped with a passive charge pump, such as WISP4.1 since Dewdrop requires directly measuring the charging rate of the reservoir capacitor—charge storage element. In the follow-up, WISP version 5.1, the passive charge pump is replaced with a S-882z active charge pump and the reservoir capacitor is only connected to the load when $V_{cap}$ developed across the capacitor exceeds the reference voltage of 2.4 V ($V_{ref}$). Consequently, in WISP5.1LRG the voltage delivered to the microcontroller is a sharp step-up, rather than a ramp-up function related to harvested power. Therefore, the charging-up process cannot be directly monitored by the technique in Dewdrop.

APPENDIX D

POWERING CHANNEL STATE MEASUREMENT AND POWER AWARE EXECUTION MODEL (PAM)

Observation. Generally, increasing distance of the token from a powering source lowers the harvester output power, RSSI and Read Rate of a given token.

Proposition. Measure powering channel state from the token is the most reliable measure of power available at a device.

Validation.

\[ RSSI = P_i G_t^2 c_{path} K \]

where \( G_{path} = \left( \frac{\lambda}{4\pi_d} \right)^2 |H|^2 \) (1)

\[ H = 1 + \sum_{i=1}^{N} g_i^2 \Gamma_i d_o e^{-j(k(d_i-d_o))} \] (2)

Although RSSI or received message rate (Read Rate) measured by an RFID reader (Server) could provide a simple method to measure the powering channel state at a CRFID transponder, we observed these measures to be highly unreliable. This can be mostly understood by considering the complexity of the signal propagation model—see equations (1) to (2) for details. We can see that RSSI depends not only on the transmit power $P_t$, the transmitter antenna gain $G_t$ and backscatter coefficient $K$, but also the path gain $G_{path}$. However, $G_{path}$ depends on signal wavelength $\lambda$, line of sight distance $d_0$ and the multi-path factor $H$; where $H$ is a complex function of angle alignment of the transmitter $q^T_t$ and the device $q^T_i$, angle-dependent reflection coefficient $\Gamma_i$ of $i$-th object, $i$-th path length for a total of $N$ multi-paths—and the influences from the random access nature of the media access control protocol used by the RFID air interface affecting RSSI and read rate measurements.

Therefore, the powering channel state is best estimated by the field deployed CRFID device harvesting available power at the device.

Thus, we introduce a power aware execution model where:

- The powering channel state at a CRFID tag is measured by the device using a single measurement of harvested power at boot-up (called a Power Sniff denoted as $V_{t_i} \leftarrow$ SNIFF($t_i$) in the update scheme). The voltage measure, $V_{t_i}$, is used to estimate the power that can be harvested by a given CRFID device in the field; and
- The workload of scheduling execution of on-device tasks is determined by the resourceful Server (RFID reader and network infrastructure) as opposed to the resource limited CRFID device based on the channel state measurements from a CRFID.

We consider a harvesting device operating under the commonly used charge-burst mode where charge is first accumulated in a storage element—often a capacitor—and charge is released for useful work when an adequate mount of charge (measured in terms of the voltage) is reached at the charge storage element. Our power aware execution model (PAM) requires the Server (RFID reader and/or host) involved in the update to derive two parameters: i) time estimation to charge to a set voltage ($V_t$); ii) time estimation to a brown-out ($t_b$) based on the CRFID reported measurement $V_{t_i}$. Here, we reason that the distance between the antenna and the given CRFID device does not change during a given update session. Therefore, the power estimated at the beginning of the session is valid during the entire session.

Unfortunately, the RF energy harvester on a CRFID device is a non-linear circuit component whose output voltage
changes over time as input RF power level varies. Therefore, it is non-trivial to model the RF energy harvester [38]. Therefore, instead of relying on an analytical model, we adopt an experimental method to derive the parameters for PAM empirically. We measure, in repeated measurements, the output voltage generated by the power-harvesting network on the WISP CRFID. We also measure the expected workload we can obtain from a CRFID device, before a brownout causes power loss. We extrapolate from these measurements to construct an empirical model for the PAM() function employed by the Server to determine the best set of execution parameters from the reported voltage \( V_t \) at runtime.

As depicted in Fig. 17 (a), the output voltage from the charge pump grows at different rates and as a function of received power. The traces do not intersect, therefore, if we measure the charge pump output voltage at an early time, e.g. 30 ms as labeled in the picture, we can obtain a voltage across the reservoir capacitor \( V_{cap} \), with which we can predict the time required for the reservoir capacitor to be charged to a certain voltage level. The charging rate of a capacitor becomes slower following a logarithm trend. It is too conservative to use the time to charge to nearly 100% saturated voltage; we empirically determined an adequate LPM time. We use the time to charge to approximately 63% of the saturated voltage, then compared to waiting for a nearly fully charged capacitor, we can reduce charge time by 75% and still accumulate adequate energy to execute the chunk of task under the active time period \( t_{active} \).

The time before brownout is also a function of received power. We can observe in Fig. 17 (b), when the powering condition is good, the CRFID device can execute the MAC computation we employed for the load, continuously; starting from \( t_a = 110 \) ms without power failure. However, the device starts to fail or brown-out causing a power loss at \( t = 142.92 \) ms, giving a time to brown out of \( t_b = t_a + 32.93 \) ms for \( V_t \) below 2.183 V. As expected, we can see that \( t_b \) decreases as the received power decreases.

**PAM function formulation.** From our results, we can conclude: i) for \( V_t \geq 2.393 \) V, the CRFID token may continuously operate with no power loss. In such cases, \( t_{LPM} = 0 \), and \( t_{active} = \infty \) is used (execution does not need to be altered); ii) for \( V_t \) within 2.183 V and 2.393 V, we can employ \( t_{LPM} = 10 \) ms and \( t_{active} = 29 \) ms (90% the measured \( t_b \) ) for a conservative approach to prevent power failures; iii) for \( V_t \) within 2.143 V and 2.183 V, use \( t_{LPM} = 15 \) ms and \( t_{active} = 14 \) ms; iv) for \( V_t \) within 2.140 V and 2.143 V, use \( t_{LPM} = 25 \) ms and \( t_{active} = 11 \) ms; and v) if \( V_t \leq 2.140 \) V, then the CRFID device cannot accumulate adequate energy under such a condition to complete a computation intensive task, and we strongly suggest to not perform a code update in this case. We describe \((t_{active}, t_{LPM}) \leftarrow PAM.Get(V_t)\) function in equation (3).

**APPENDIX E**

**Transponder Modes & Broadcast Channel**

Stork [7] proposed exploiting promiscuous listening by choosing one in-field token (CRFID) to stay in the non-overhearing mode and the rest in overhearing (observer or promiscuous listening) mode to create a logical broadcast channel. This method overcomes the unicast media access layer protocol to facilitate wireless code dissemination to multiple CRFID devices. Building upon Stork, our Pilot-Observer mode (Section 3.2.2) makes a key improvement. In contrast to Stork [7], for the token under Non-overhearing/Pilot mode, instead of selecting the first device responding to an interrogation signal from the Server, we elect the device with the lowest reported voltage (\( V_t \)) as the pilot token. The similarities and differences between our work and the Stork are summarized in Table 5.

This method forces the broadcast session to be driven by the device with the lowest available energy, and the highest probability to brownout; thus, increasing the chance of all non responding tags remaining in synchronicity with the the processing of the broadcasted firmware, simply because these devices are able to harvest more power than the pilot token whilst also not having to respond to the Server.

**APPENDIX F**

**Pilot Election Experiments**

We have collected experiments for 20 cm, 30 cm, 40 cm and 50 cm as shown in Fig. 18. Generally, at 20 cm and 30 cm, all methods can succeed, with little differences in terms of the number of attempts and latency. In comparison, all methods failed to update all four tokens in 10 attempts at 50 cm; although several devices were often updated, no attempt resulted in all four tokens being updated at this powering level.
hence the success rate is reported as zero. However, in the regions where devices are likely to operate at the threshold of powering, seen at 40 cm in our experiments, our proposed pilot election method performs best. Further, the proposed method is also seen to perform more consistently; indicated by the consistent success rate across different powering conditions achieved with different distances.

**APPENDIX G**

**EXECUTION OVERHEAD FOR RECEIVING BROADCAST PACKETS**

It is non-trivial to analyze the clock cycles for receiving a packet and sending a reply, as opposed to other tasks, as they are executed under a constant clock speed. Notably, the CRFID tokens do not have a hardware implementation of the wireless communication protocol. The RFID communication protocol is implemented in software. Since RFID communications require strict timing requirements, the CPU clock is dynamically configured and the relevant source code is written in assembly language to meet the strict timing requirements. For example, when the device is receiving a packet, the CPU works at 16 MHz. When the device is sending a reply by modulating its antenna impedance, the CPU works at 12 MHz. So it is difficult to employ our previous method to predict clock cycles by monitoring GPIO pins.

To overcome the above challenge, we used debugger tools to read the CRFID device’s internal states by inserting three breakpoints: Breakpoint 1: before the receiving routine is called; Breakpoint 2: in between the receiving routine and the reply routine; Breakpoint 3: after the reply routine (as illustrated in Fig. 19). Clock cycles for receiving and replying can be acquired by looking at the clock profile counter at each breakpoint.

The SecureComm command in the EPC Gen2 specification is yet to be widely supported in commercial RFID hardware. Therefore, as we mentioned in Section 3.2.2, we implement this command over the existing BlockWrite specified to support variable payload size as described in [54]. However, the Impinj R420 RFID reader we used in experiments implements it in a distinct manner. Irrespective of the specified payload size, the Impinj R420 reader (software version 5.12.3.240) always splits the payload into multiple BlockWrite commands, each command carrying a payload of only 2 Bytes [54]. Further, busy waiting is used while receiving a command from the RFID reader (for example, at https://git.io/J1j08). Hence, clock cycle results can vary from measurement to measurement. Hence, in our experimental results, we report the average clock cycles for such BlockWrite commands over 100 repeated measurements. We summarize the results below:

- Pilot token’s cycles to receive a BlockWrite packet (with 2 Byte payload): 23,082
- Pilot token’s cycles to send a reply to the BlockWrite packet: 1,131
- Observer token’s cycles to receive a BlockWrite packet (with 2 Byte payload): 22,002
- Observer token’s cycles to send a reply to the BlockWrite packet (with 2 Byte payload): 1,080 smaller than the pilot token (this number is obtained by calculating the difference between the pilot and observer tokens’ clock cycle counter at Breakpoint 2, over the average obtained from 100 measurements). This is because the observer does not need to prepare the reply packet (ACK), which requires a CRC-6 calculation, as illustrated in Fig. 19.

The total number of packets required in an update can be computed with:

\[ N_{\text{packets}} = \frac{\text{firmware size (in Bytes)}}{2 \text{ Bytes per BlockWrite command}} \]

The number predicted using the above equation is in an ideal case, the actual number may be higher considering retransmissions, for example, due to communications errors identified using the CRC.

**APPENDIX H**

**EXPERIMENT SETUP TO ACCESS TOKEN’S INTERNAL STATE**

Some of our experiments require to measure the internal states of the token. For example the impact of four key device tasks on power-loss and the evaluation of our proposed power PAM method in Section 3.2.2. However, we do not have a precisely controlled RF environment (i.e., anechoic chamber) to remove the impact of the multipath signals constructively and destructively interfering with the RF powering of a device.

The measurement processes for Fig. 5 and Fig. 7 were different and complicated by the probes and wires that we need to attach to the device, the Digital Storage Oscilloscope (DSO) we need to keep near the setup as well as the close proximal presence of the researcher to operate the DSO to enable taking the measurement as shown in Fig. 20.

To try to mitigate the influence of factors discussed above, we conducted these experiments following the method we describe below:

- Ensure we used the same CRFID device for both experiments.
- Try our best to keep the multipath environment the same across the two experiments. Hence, instead of adjusting the distance (which suffers from different multipath reflection and interference) and the changing positions of the probes and wires, we have the CRFID device fixed at 20 cm above the reader antenna, and adjusted the transmit power of the RFID reader following the method in [54].

We can employ this method because, according to the free-space path loss equation [36] given below, adjusting the transmit power \( P_t \) of the RFID reader has a similar impact on the received power \( P_r \) as changing the distance \( d \). Because, the RF wavelength \( \lambda \) is relatively constant (notably RFID employs frequency hopping regulations) whilst the RFID reader antenna gain \( G_r \) and CRFID device antenna gain \( G_t \) are fixed.

\[ P_r = P_t G_t G_r \left( \frac{\lambda}{4\pi d} \right)^2 \]

Notably, in the evaluation of PAM, what we are interested in is the available harvested power, distance is just one factor we can use to control the available power at the device in our experiments. Adjusting the transmit power endows us with a more accurate form of control over the available power as that can be done using the RFID reader software,
Fig. 18. Evaluation of the pilot token selection strategies we propose. Four tokens were placed at 20 cm, 30 cm, 40 cm and 50 cm above a reader antenna. The pie chart shows the number of attempts to have all 4 CRFID devices or tokens updated. The scatter plot shows the corresponding latency for successful updates. The results are obtained over 100 repeated measurements, where each measurement included 10 attempts to update all four CRFID devices. The bar graph denotes the number of successful updates—defined as all four tokens being updated over the 100 repeated measurements. Here (mean, standard deviation) latency statistics are given in red text.

programmatically, and without interfering with the devices setup (such as changing distances and the arrangement of the probe wires and the multi-path environment).

### APPENDIX I

**FIRMWARE UPDATE TO MOBILE TOKENS**

We tested firmware updates to mobile CRFID devices. We rotated the rotor by hand, with a rotation speed of approximately 1 RPM (revolutions per minute) and conducted 100
Fig. 19. Method to measure clock cycles for receiving a packet and acknowledging a received packet.

Fig. 20. Experiment setup and instrumented CRFID device used for the experiments summarized in Fig. 5 and Fig. 7. Notably conducting the experiments require a researcher to be seated next to the DSO. The probes, the changing positions of the wires leading from the probes, especially at different distances, and the orientation of the researcher significantly impacted these measurements.

Repeated firmware updates to the four CRFID devices in the rotor blades (as illustrated in the video [https://youtu.be/AVrfl0rNM0z8](https://youtu.be/AVrfl0rNM0z8)). Here, as in other experiments, for each firmware update, the Host makes 10 attempts to update all 4 devices. The result in Fig. 21 shows that 3 updates resulted in disseminating firmware to all four tokens, and in 51 updates, at least one token is updated. We can conclude that updating firmware to mobile CRFID devices is possible but the success rate can be expected to reduce dramatically.

Fig. 21. Attempt to update firmware while the UAV rotor is rotated by hand at approximately 1 RPM. The pie chart shows the number of CRFID devices updated in the 100 repeated firmware update executions.