Wisent: Robust Downstream Communication and Storage for Computational RFIDs

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Abstract

Computational RFID (CRFID) devices are emerging platforms that can enable perennial computation and sensing by eliminating the need for batteries. Although much research has been devoted to improving upstream (CRFID to RFID reader) communication rates, the opposite direction has so far been neglected, presumably due to the difficulty of guaranteeing fast and error-free transfer amidst frequent power interruptions of CRFID. With growing interest in the market where CRFIDs are forever-embedded in many structures, it is necessary for this void to be filled. Therefore, we propose Wisent—a robust downstream communication protocol for CRFIDs that operates on top of the legacy UHF RFID communication protocol: EPC C1G2. The novelty of Wisent is its ability to adaptively change the frame length sent by the reader, based on the length throttling mechanism, to minimize the transfer times at varying channel conditions. We present an implementation of Wisent for the WISP5 and an off-the-shelf RFID reader. Our experiments show that Wisent allows transfer up to 16 times faster than a baseline, non-adaptive shortest frame case, i.e. single word length, at sub-meter distance. As a case study, we show how Wisent enables wireless CRFID reprogramming, demonstrating the world’s first wirelessly reprogrammable (software defined) CRFID.

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I. INTRODUCTION

Computational RFIDs (CRFIDs) and other wireless, transiently-powered computing devices are emerging platforms that enable sensing, computation and communication without batteries [1]. CRFIDs have been proposed for use in scenarios such as structural health monitoring, in which a device may be embedded in a reinforced concrete structure [2], or implanted scenarios involving tasks such as blood glucose monitoring [3] or pacemaker control [4], where access to the device requires an expensive and/or risky surgery. In these deeply embedded applications, maintenance of the device is difficult or impossible, making battery-free operation attractive as the battery maintenance requirement is avoided entirely.

However, as the complexity of use cases for CRFIDs grow, there is another emerging maintenance requirement: the need to patch or replace the firmware of the device, or to alter application parameters including the RFID radio layer controls. In current CRFIDs, maintenance of firmware (due to e.g. errors) requires a physical connection to CRFID, nulling the main benefit of battery-free operation.

Existing CRFIDs have no means for reliable high-rate downstream (i.e. RFID reader to CRFID) wireless communication and storage. This makes downstream protocols for CRFIDs a potent area of study. Current CRFIDs use UHF RFID standards, such as EPC C1G2 [5], designed to support inventory management applications with minimal computational and data transfer requirements [6], [7]. Any UHF RFID network is built around an interrogator, which provides power to tags in the vicinity, and which can both send/receive data to/from those tags. The uplink from tag to reader is accomplished through backscatter communication, in which the tag modulates its reflection of the reader’s carrier signal in order to communicate—with orders of magnitude less power than a conventional radio. The reader is a wall socket-powered device, while the tag is a highly energy-constrained energy-harvesting battery-free platform, resulting in frequent power supply breaks, see Figure 1.

A. Problem Statement

In CRFIDs, downstream transfer functionality would enable (i) the processing of data sent wirelessly, (ii) CRFID to CRFID data transmission, and most importantly (iii) wireless reconfiguration, including reconfiguration of the communication protocol itself (e.g. demodulation, decoding). In this work, we therefore pose the following research question: How to enable robust and fast downstream communication for CRFIDs?

There are two challenges in enabling CRFID downstream.

Challenge 1: Existing CRFIDs rely on the suboptimal downstream communication capability of the EPC C1G2 standard. In fact, EPC C1G2 does not have built-in support for fast transfers of large portions
of data from the reader to the tag. Building a replacement for reader to CRFID tag communication protocol would indeed improve communication capabilities and performance, however, doing so would reduce compatibility with existing EPC C1G2-compliant RFID systems, which represent a significant amount of existing infrastructure. Therefore, designing a protocol extension on top of EPC C1G2 is the natural path (although a difficult one) towards a capable yet practical downstream CRFID protocol.

**Challenge 2:** Transient power availability in CRFIDs means that tags will often lose power, and in turn processor state [10] (again see Figure 1). Introduction of FRAM in latest CRFID release, i.e. WISP 5 [8], alleviated slow read/write operations of non-volatile flash memory of previous CRFID releases [11]. The question remains whether FRAM will suffice for repetitive data storage operations in CRFID.

**B. Contributions**

While the current focus of CRFID systems lies in improving upstream communication, see e.g. [12]–[14], due to the mentioned challenges, to the best of our knowledge, there has surprisingly been no work focusing on downstream communication, where CRFIDs are on the receiving end of large data transfers. To fill this void our contributions are:

**Contribution 1:** We leverage EPC C1G2 functionality to implement and evaluate multi-word downstream data transfer, i.e. longer than the de facto limit of a 16-bit word (2 bytes). Experimentally we show threefold improvement of raw downstream throughput. We also show that the error rate of multi-word messages transferred by the reader to the CRFID reduces throughput instantly to zero at long reader to CRFID distances.

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Fig. 1. Example distribution of CRFID (WISP 5 [8]) available harvested energy between periods of state loss (experiment details: [9]). Energy is mapped into the number of instruction cycles WISP 5 can achieve per burst with its default hardware configuration. The frequent state loss makes reliable bulk data transfer hard.
**Contribution 2:** We design, implement and experimentally evaluate Wisent\(^1\)—a downstream-oriented protocol for CRFIDs. Wisent allows for an adaptation of the length of the reader message size based on the received message rate at the CRFID to keep the transfer speed high, while minimizing the data transfer errors. Furthermore, utilizing FRAM’s capability of random-access instantaneous read/write operations without memory block erasure available in WISP 5 [8], we enhance Wisent with a mechanism for fast storage and verification of large portions of data.

**Contribution 3:** We implement and demonstrate the world’s first fully wirelessly-reprogrammable CRFID, enabling software-defined CRFID with truly reprogrammable radio stack.

The remainder of the paper is organized as follows. Related work is described in Section II, while Section III introduces the CRFID downstream protocol preliminaries. Section IV outlines Wisent design and its implementation. Experimental results and evaluation of CRFID downstream transfer improvements through the EPC C1G2 BlockWrite implementation, Wisent itself, and the use of Wisent in wireless reprogramming scenarios are presented in Section V. Future work is discussed in Section VI, while the paper is concluded in Section VII.

Finally, we remark that in the spirit of the results reproducibility, source code for Wisent, measurement data and log files are available upon request or via [9].

II. RELATED WORK

A. Data Transfer on CRFID

As we noted earlier, no existing work, to the best of our knowledge, targets fast and reliable reader-to-CRFID communication. On the other hand, various CRFID-related works discuss data schemes for upstream (tag-to-reader) data transfers. Examples of such work include HARMONY [13], a data transfer scheme implemented on the WISP 4.1 with the purpose of reading bulk data, and Flit [14], a coordinated bulk transfer protocol implemented on the Intel WISP. A recent work [12] considers the image data transfer from the camera-enabled WISP to an RFID host. For the interested reader we refer to [15], [16], where system-level evaluation of link layer performance of EPC C1G2 has been investigated. We also refer to BLINK [17]: the only known alternative to EPC C1G2 in the context of CRFID, and to [18], where a modified EPC C1G2 was used to speed up tag access operations.

B. Wireless Reprogramming of Communication Platforms

The concept of wireless reprogramming and over-the-air (OTA) firmware update mechanisms is well researched in non-CRFID fields, namely in cellular systems and wireless sensor networks (WSNs). For

\(^1\)Wisent, i.e. the European Bison, is a wordplay on ‘Wirelessly sent’.
example, a software redistribution architecture for mobile cellular terminals was discussed first in [19], while code distribution architecture for WSNs has been discussed in [20]. However, wireless reprogramming is completely new to the CRFID field and the only two relevant works we are aware of are Bootie [11] and FirmSwitch [21]. Bootie describes a proof-of-concept bootloader for CRFIDs and a preliminary design of a firmware update protocol that allows Bootie to accept and install firmware updates wirelessly. However, its wireless protocol proposal neglected error handling and bookkeeping, has not been implemented or tested and no results on its performance exist thus far. FirmSwitch introduced and implemented a wireless firmware switching mechanism for CRFID. Unfortunately FirmSwitch does not deliver the most significant benefit of the reprogramming, as only pre-installed programs can be selected by its CRFID bootloader. Neither OTA firmware updates nor fast/reliable transmission protocols were proposed therein.

III. DOWNSTREAM CRFID PROTOCOL: PRELIMINARIES

A. Host-to-CRFID Communication: System Overview

Three fundamental components of a typical CRFID system are (i) a host machine—any device that is able to communicate with the RFID reader over any popular physical interfaces such as Ethernet or Wi-Fi, (ii) an RFID reader (connected to an antenna) and (iii) a CRFID tag, see Figure 2. All communications from a host to a tag are first sent to the reader. In the context of the EPC C1G2 [5] standard, the Low Level Reader Protocol (LLRP) [22] specifies a network interface for such communication. The reader then issues EPC C1G2 commands corresponding to the LLRP messages it received from the host. Naturally, EPC C1G2 and LLRP communication primitives enforce limitations that have to be taken into account in any CRFID protocol design. We define them below.
Fig. 3. LLRP AccessSpec reader state machine [22, Fig. 10] utilized in enabling continuous host-to-reader bulk data transfer following Proposition 1. The dashed lines represent optional state transitions.

B. Reader-to-Tag Communication: EPC C1G2

There are only two commands in the EPC C1G2 standard with the purpose of sending data from the reader to a tag: Write and BlockWrite [5]. While Write is a mandatory command in the EPC C1G2 specification (i.e. tags conforming to the standard must support these commands [5, pp. 13]), BlockWrite is specified as optional, and prior to this work its implementation was nonexistent in CRFIDs. Data transfer with Write is limited to only one word at a time. To achieve data transmission rates beyond what is supported with Write, an implementation of BlockWrite for CRFIDs is fundamentally needed. Length-wise, BlockWrite can be orders of magnitude longer than Write. It is thus far more susceptible to channel errors (induced by e.g. CRFID movement). Therefore its performance must be well understood to maximize the transfer speeds for CRFID downstream protocols built on top of EPC C1G2.

C. Host-to-Reader Communication: LLRP

Despite LLRP’s large overhead, it is possible to use it as part of a downstream protocol.

**Proposition:** Continuous host-to-reader data streaming is enabled in LLRP by issuing a train of AccessSpec commands.

**Evidence:** A host machine can command a reader to start an inventory session on tags only by enabling a ROSpec [22, Sec. 6]. An AccessSpec can optionally be included inside a ROSpec to make a reader issue an access command (e.g. Write) on tags. To change the current command or its properties (e.g. the amount of words or content of a BlockWrite) issued by the reader, the AccessSpec must be changed. To achieve this, the host machine needs to tell the reader to first delete the current AccessSpec, add a new one, and finally enable it (see Figure 3). Alternatively, an AccessSpecStopTrigger can be specified by the host to make a reader autonomously delete an AccessSpec once its command has been performed OperationCountValue times by the tag. Using both principles, it is possible for a host to send multiple AccessSpecs in a continuous fashion to a reader to effectively enable a data stream. □
D. Design Requirements

From the challenges that arise in Section I and the limitations found in CRFID systems, we can now formulate the design requirements for a downstream CRFID protocol. It must be (i) built on top of EPC C1G2 and LLRP; (ii) able to send large portions of data from a host to a CRFID via a reader; data transmission and storage must be reliable and (iii) tolerate interruptions to operating power; (iv) must tolerate changes of distance of the CRFID platform to the reader’s antenna. Additionally, to achieve transmission rates beyond the limitations set by EPC C1G2 Write, (v) the BlockWrite command should be enabled. Furthermore, to alleviate the negative effect of transient power on repetitive tasks in write operations to CRFID’s memory, such protocol must use (vi) CRFID platforms with non-volatile FRAM memory. We remark that although a CRFID system might consist of multiple tags, we design Wisent for communication with a single tag in mind2.

IV. Wisent: Design and Implementation

A. Wisent Hardware and Software

As a host we use a x86-64 computer with an Intel i5-3317U processor running Ubuntu 14.04. As an RFID reader we use an off-the-shelf 915 MHz Impinj Speedway3 R420 with firmware version 4.8.3 connected to a Laird S9028PCR 8.5 dBic gain antenna. As a CRFID device we use a WISP 5 [8] with TI MSP430FR5969 MCU which has 64 KB of FRAM4. To initially program the WISP with Wisent we use a MSP430 Flash Emulation Tool (FET), in combination with TI Code Composer Studio (CCS), attached to the host. The FET also enables measuring the energy consumption of the WISP and inspecting WISP non-volatile memory.

To implement all necessary features of Wisent in LLRP we have extended sllurp [23]: a LLRP control library written in Python. The CRFID-side of Wisent is implemented in C and MSP430 assembly. A complete Wisent implementation amasses to 350 lines of Python and 60 lines of C in addition to 100 instructions of MSP430 assembly. Refer again to Figure 2 for our CRFID system setup used in Wisent experiments.

2Extensions of Wisent for communication with multiple tags will be discussed in Section VI.

3We have also tested Wisent using Impinj Speedway R1000 but the experimental results in this work were generated with the R420 reader only.

4Although Wisent has been tested exclusively on the WISP 5, it can be targeted towards any CRFID platform using FRAM non-volatile memory.
Fig. 4. Example record of an Intel Hex file. The numbers on top of each field denote the index of the ASCII symbol in the record and the values inside each field denote example content. The length field specifies the byte count in the data field, while the address field represents the destination address for the data in the CRFID memory. Gray fields are not used in Wisent messages.

(a) EPC C1G2: standard versus Impinj readers; cmd: command (generic), Bwr[x]: xthBlockWrite

(b) Wisent Basic: :02AADD00BBCCF0 record

Fig. 5. Wisent message transfer case studies: (a) Difference of using EPC C1G2 commands as specified by the standard [5] (1–3) and BlockWrite with WordCount=2 as observed at Impinj readers (4–7). The reader reports a no tag seen (2,7) if the tag did not receive the command at all. An error is reported instead if the tag received the command but processed it incorrectly (3,5,6). Only success reports (1,4) are counted towards the OperationCountValue of individual AccessSpecs; (b) Example of a Wisent Basic communication sequence of messages constructed from a record with content :02AADD00BBCCF0.

B. Wisent Components

1) Message Format: To implement fast reader-to-tag transmission, any bulk data that is to be sent to CRFID (e.g. regular file or firmware) should be presented in one specific format. For that purpose we utilize the Intel Hex file format due to its popularity, noting that other formats such as TekHex or Motorola-S [24, Sec. 12.12] can be also supported. An Intel Hex file is divided into lines, called records, and contain fields of information about the data, see Figure 4, which are later parsed for transfer as described below.
2) Message Definitions: We define \( m \): a Wisent message, i.e. message sent from the host to CRFID as content for a Write or BlockWrite command that is constructed by the host as follows. First, information is taken from the length, address and data fields of each Intel Hex file record \( i \), being the only necessary fields for our implementation. We denote the data that is taken this way as a matrix \( I \), from which \( I(i,j) \) is the \( j \)-th chunk in row \( i \) of size \( S_p \) words. The value of \( S_p \) depends on which of the two commands, leveraged by the two distinct versions of Wisent described in subsequent Section IV-C and Section IV-D, the content is constructed for. To a constructed \( I(i,j) \), we add a header with information to identify and instruct the CRFID as to how the remaining part of the message, i.e. the payload, should be handled. Details on the header and payload content, including payload handling, shall also be discussed in Section IV-C and Section IV-D, as they are also Wisent-version dependent.

The next message to be sent is defined as

\[
m_{\text{next}} = \begin{cases} 
I(1,1) & \text{if } m = \varepsilon, \\
I(i,j + 1) & \text{if } j \neq \text{EOL}, \\
I(i + 1,1) & \text{if } j = \text{EOL}, \\
\emptyset & \text{if } i = \text{EOF}, 
\end{cases}
\]

where \( \varepsilon \) is the undefined message and EOL and EOF is the Intel Hex end of the record and end of file, respectively.

The backscattered EPC field of the CRFID is utilized for message verification purposes. During the construction of each message, the host generates verification data that is compared with the EPC in a tag report from the reader. However, since the EPC is backscattered before a command that accesses the tag is executed [5, Annex E] (e.g. Write, BlockWrite), an EPC after that command is needed to verify the current message. The host receives a positive acknowledgment (ACK) of a message if this EPC matches the verification data and a negative acknowledgement (NACK) otherwise.

The OperationCountValue (OCV), described in Section III-C, acts as an upper bound of the operation frame [25, Fig. 4.3] in which a message \( m \) is actively transmitted by the reader through a command operation. Unlike ACKs and NACKs, which depend on following EPC fields, the result of a command operation is reported before the next EPC arrives, and only successful commands count towards the OCV, see Figure 5(a). However, such a report contains an EPC regardless of result and therefore, the report of a successful operation, e.g. Write, can contain a NACK and contrarily a report of an erroneous
Protocol 1 Wisent Basic

1: $R_{\text{count}} \leftarrow 0$  \hspace{1cm} \triangleright \text{Host events}
2: $m \leftarrow m_{\text{next}}$  \hspace{1cm} \triangleright \text{See eq. (1)}
3: \text{SEND}(m)
4: \textbf{while} $R_{\text{count}} < R_{\text{max}}$
5: \hspace{1cm} \textbf{upon} ACK:
6: \hspace{2cm} $R_{\text{count}} \leftarrow 0$
7: \hspace{2cm} $m \leftarrow m_{\text{next}}$  \hspace{1cm} \triangleright \text{See eq. (1)}
8: \hspace{2cm} \text{SEND}(m)
9: \hspace{1cm} \textbf{upon} TIMEOUT:
10: \hspace{2cm} $R_{\text{count}} \leftarrow R_{\text{count}} + 1$
11: \hspace{2cm} \text{SEND}(m)
12: \hspace{1cm} \textbf{upon} RECEIVE($m$):
13: \hspace{2cm} EPC $\leftarrow \text{HANDLE}(m)$
14: \hspace{2cm} \text{BACKSCATTER(EPC)}  \hspace{1cm} \triangleright \text{Tag events}

operation can embed an ACK$^5$.

The \textit{message frame} of a message $m$ starts as soon as the host sends that message to the reader. When $m$ is acknowledged by the CRFID, the message frame of $m$ ends and the host moves on to the message frame of $m_{\text{next}}$, commanding the reader to delete the AccessSpec containing $m$ before sending $m_{\text{next}}$. However, there is a delay before this deletion is processed by the reader and thus a delay before the start of the operation frame of $m_{\text{next}}$. Because of this, the operation frame of $m$ overlaps with the message frame of $m_{\text{next}}$ causing ACKs for $m$ in the overlap to be NACKs for $m_{\text{next}}$.

If too many NACKs, defined by $N_{\text{threshold}}$, are observed, a \textit{timeout} is generated and the message will be resent up to a maximum, $R_{\text{max}}$, number of times. If after the maximum amount of resends, the message is still not received, the Wisent transfer is aborted and ends up in a failure. Even though power failures as a result of transient power (see Figure 1) are accounted for by NACKs, separation of the CRFID from the antenna for a prolonged period of time (which results in a transfer failure) are not. This issue will be discussed in Section VI.

C. Wisent: Basic Protocol

The \texttt{Write} command limits a message to only one word of content. Due to the small size of the message, we propose a copy of the message to be kept by the host as verification data to compare with the EPC. By fitting a single byte header in such a message, only one byte remains for the payload, i.e. $S_p = 0.5$ words. We propose a non-ambiguous header that describes the payload with data $I(i,j)$ obtained

$^5$EPC of previously reported (successful) operation is piggybacked \textit{during the next operation} (which happens to be unsuccessful) as an ACK.
Protocol 2: Wisent EX

```plaintext
1: $R_{\text{count}} \leftarrow 0$  \hspace{1cm} \triangleright \text{Host events}
2: $M_{\text{count}} \leftarrow 0$
3: $S_p \leftarrow S_{\text{max}}$
4: $m \leftarrow m_{\text{next}}$  \hspace{1cm} \triangleright \text{See eq. (1)}
5: SEND($m$)
6: while $R_{\text{count}} < R_{\text{max}}$
7: \hspace{1cm} upon ACK:
8: \hspace{2cm} $R_{\text{count}} \leftarrow 0$
9: \hspace{2cm} if $M_{\text{count}} > M_{\text{threshold}}$ then
10: \hspace{3cm} THROTTLE($S_p$, up)  \hspace{1cm} \triangleright \text{See eq. (3)}
11: \hspace{2cm} $M_{\text{count}} \leftarrow 0$
12: \hspace{2cm} else
13: \hspace{3cm} $M_{\text{count}} \leftarrow M_{\text{count}} + 1$
14: \hspace{2cm} $m \leftarrow m_{\text{next}}$  \hspace{1cm} \triangleright \text{See eq. (1)}
15: \hspace{2cm} SEND($m$)
16: \hspace{1cm} upon TIMEOUT:
17: \hspace{2cm} $R_{\text{count}} \leftarrow R_{\text{count}} + 1$
18: \hspace{2cm} $M_{\text{count}} \leftarrow 0$
19: \hspace{2cm} THROTTLE($S_p$, down)  \hspace{1cm} \triangleright \text{See eq. (3)}
20: \hspace{2cm} $m \leftarrow I(i,j)$  \hspace{1cm} \triangleright \text{See eq. (1)}
21: \hspace{2cm} SEND($m$)
22: \hspace{1cm} upon RECEIVE($m$):
23: \hspace{2cm} EPC $\leftarrow$ HANDLE($m$)  \hspace{1cm} \triangleright \text{Tag events}
24: \hspace{2cm} BACKSCATTER(EPC)
```

from only the address and data fields. For each row $i$, two messages should be sent, each with a payload containing half of the address field and a unique header to identify which half of the address field the message contains. The following messages should include a byte from the data field as payload and a header that represents an offset of the byte to the base address. The proposed header definitions are: 

(i) \text{FD}: new line (address low byte), 
(ii) \text{FE}: address high byte, and 
(iii) 00–20 data byte with offset. For ease of explanation, an example message transfer sequence is shown in Figure 5(b).

Messages received by the CRFID are handled by a \text{HANDLE($m$)} function, see Protocol 1 (line 13), as follows. First, the integrity of a message is checked and the CRC16 checksum over data of the Write command is calculated [5, Sec. 6]. However, data written to non-volatile memory might still be corrupted in case of power failure. Therefore, the address to which the byte was written is immediately read to verify the content. Afterwards, the EPC of the CRFID is set to the header of the received message along with the read byte. Pseudocode of Wisent Basic can be found in Protocol 1.

D. Wisent EX: Extending Wisent Basic with BlockWrite

To overcome the single word limit imposed by the Write command, we have extended Wisent to make use of BlockWrite, denoted as Wisent EX, which introduces the use of a WordCount parameter.
WordCount specifies the size of a BlockWrite payload.

1) Implementation of BlockWrite: We have observed that the Impinj RFID readers do not issue the BlockWrite command as specified by EPC C1G2 [5, pp. 92]. Rather than issuing one BlockWrite command with data containing all the words, the reader issues a series of commands, see Figure 5(a), each containing one word and a sequential increasing address pointer to store the word in the memory of the tag. Because of this, the original BlockWrite from the host to the reader is not known to the CRFID, while the reader still considers the series as the instructed BlockWrite. A command operation of BlockWrite will only be reported as successful if and only if the CRFID processes each of the individual commands in the series and replied to the reader for each of these commands. To avoid extra computation on the CRFID, the CRC16 checksum of each command in the series is not calculated.

2) Verification: Because the CRC16 checksum was not calculated for BlockWrite, the communication channel is not reliable anymore. An alternative verification mechanism and checksum is necessary to secure the robustness of the communication channel and verify the data written to the non-volatile memory. We propose the use of a single byte checksum for each message that is calculated by taking the least significant byte of the sum of all bytes in message \( m \). This checksum is calculated to check the integrity of the message when received by the CRFID and after writing data to the non-volatile memory.

With message sizes that can exceed the EPC length, using a copy of the message as means for verification is no longer a viable solution. Nevertheless, a larger message size allows a header of more than one byte, that can be used instead for verification purposes and should be set as EPC by the CRFID. In such a header, we propose to include (i) the message checksum \( c \); (ii) length of the payload in bytes \( l \); and (iii) destination address of the payload. Consequently, the payload should contain data \( I(i,j) \) obtained only from the data field of Intel Hex file record, see Figure 6.

3) Throttling: We first introduce the following observation.

Lemma 1: Larger WordCount does not always correspond to faster bulk transfer rates.

\[ \text{Although Wisent EX is built utilizing this non-standard BlockWrite behavior, it would also work in combination with RFID readers that do issue BlockWrite as specified in the EPC C1G2 standard.} \]

\[ \text{Our approach follows the same method used in Intel Hex files but we are naturally aware of alternative error correction methods. Nevertheless, we will introduce another bootloader specific layer in Section V-C.} \]
Proof: We prove this observation by contradiction. For a BlockWrite command of length $L$ bits the transmission overhead is $[5, \text{Table 6.43}]$ $H = 51$ bits. Assuming a general complementary error function relating bit error to distance $d$ [26, Eq. (3)] $p_e(d) = \text{erfc}(1/d)$ a normalized BlockWrite throughput is $T(L, d) = L/(L + H)(1 - p_e(d)^{L+H})$ (compare with [26, Eq. (1)]). Now, for BlockWrite commands with data lengths $L_1 = 16$ bytes and $L_2 = 32$ bytes we have $T(L_1, d) < T(L_2, d)$ for $d = 0.2$, while for $d = 0.5$ the opposite holds, which completes the proof.

Following the above observation we propose the use of a throttling mechanism to adjust $S_p$, the payload size of messages, which is initialized to a user defined value $S_{\text{max}}$. Given the amount of words $S_t$ in data row $I(i)$, we construct a set $T_t$ for $S_p$ values as

$$T_t = \left\{ S_p : S_p = \left\lceil \frac{S_t}{n} \right\rceil , \quad n, S_t \in \mathbb{N}^+, n \leq S_t, \right\}$$

where $n$ represents the number of data chunks, and in turn messages, in which that row should be split. The throttling function is then defined as

$$\text{THROTTLE}(S_p, \rho) = S_{p+1} \in T_t,$$

where $\rho = \{\text{up}, \text{down}\}$, with $S_{p+1} > S_p$ if throttling up, and $S_{p+1} < S_p$ if throttling down.

If the need for a resend is perceived, $S_p$ is throttled down to decrease load on the communication channel. On the other hand, $S_p$ is increased upon $M_{\text{threshold}}$, a threshold of consecutive successful messages. With this, the full description of the protocol is complete, refer to pseudocode in Protocol 2.

V. EXPERIMENT RESULTS

A. Evaluation of BlockWrite

We first evaluate the performance of the BlockWrite alone, as it is the basis of Wisent. The experiment setup is as shown in Figure 2 and explained in Section IV-A. The whole measurement setup was located inside of an university laboratory and each of the experiments were repeated five times.

1) Maximum Word Size of BlockWrite: EPC C1G2 implies a maximum value of 255 words for WordCount by the 8-bit length of the WordCount header field. We have tested multiple WordCount values and found a R420 reader is not able to issue more than 32 words at a time.

2) BlockWrite Performance Metrics: During our experiments we let the reader issue a single BlockWrite with a set WordCount for each experiment. Such operation is repeated for a duration of ten seconds, i.e. the host sends an AccessSpec with a BlockWrite to the reader without an AccessSpecStopTrigger and halts after ten seconds, over multiple distances $d = \{20, 30, \ldots, 60\} \text{ cm}$ from the tag to the antenna.
Fig. 7. Success operations per second, efficiency and throughput of a single BlockWrite as functions of WordCount over various distances.
TABLE I
FUNCTION PARAMETERS FOR $f_{\psi_t}(x)$ AND $g_{\eta}(x)$ AND $R^2$ FOR $h_{\theta}(x)$

| $d$ (cm) | $a_{\eta}$ | $b_{\eta}$ | $a_2$ | $b_2$ | $c_2$ | $R^2$ |
|----------|------------|------------|-------|-------|-------|-------|
| 20       | 0.0138     | 0.9448     | 170.3735 | 0.4184 | -22.1623 | 0.9176 |
| 30       | 0.0163     | 0.9401     | 166.3176 | 0.4523 | -16.6735 | 0.8627 |
| 40       | 0.0168     | 0.9270     | 164.6218 | 0.4341 | -18.7205 | 0.7716 |
| 50       | 0.0204     | 0.9056     | 158.3378 | 0.4909 | -10.9255 | 0.4504 |
| 60       | 0.0503     | 0.8710     | 122.2697 | 0.7347 | 11.0553 | 0.8553 |

We propose the following set of performance criteria of the BlockWrite: (i) number of success operations per second (SOPS) defined as $\psi_s = n_s / t$ where $n_s$ is the number of success reports and $t$ (sec) is the duration of the experiment; (ii) the number of total operations per second (TOPS) defined as $\psi_t = n_t / t$, (iii) efficiency defined as $\eta = \psi_s / \psi_t$, and (iv) throughput defined as $\theta = 2x\psi_s$ (B/sec), where $x$ is the WordCount value (since each word is 2 bytes long).

3) BlockWrite Performance Results: In Figure 7(a) we show that we are able to improve throughput of reader-to-CRFID communication manyfold compared to a single word length. While there is only minor efficiency degradation between 20 and 50 cm (Figure 7(b)), the effect of issuing BlockWrite with large WordCount can clearly be seen if the WISP is moved too far away from the antenna. The efficiency is much impacted larger at 60 cm, possibly preventing further usage of such WordCount values in Wisent EX messages.

4) BlockWrite Performance Metrics Model: From the measured data presented in Figure 7 we conjecture that simple functions can be used to describe all experimentally obtained statistics, which can be used in future analytical studies. For this purpose we propose a model for which we introduce $f_{\psi_t}(x)$ and $g_{\eta}(x)$, which describe the relations between selected word size $x$ and $\psi_t$ and $\eta$, respectively. From these functions, $f_{\psi_s}(x)$ and $h_{\theta}(x)$ follow, describing the respective relations for $\psi_s$ and $\theta$. We then have

$$f_{\psi_t}(x) = \frac{a_2}{d^2} + c_2,$$

$$g_{\eta}(x) = \frac{f_{\psi_t}(x)}{f_{\psi_s}(x)} = -a_{\eta}x + b_{\eta},$$

$$h_{\theta}(x) = 2xf_{\psi_s}(x),$$

with all associated parameters given in Table I. Using MATLAB R2015a we have calculated the above fit accuracy via coefficient of determination, $R^2$, for all fitted functions over all measured distances $d$. For $f_{\psi_t}(x)$ the mean value of $R^2$ for all distances is $\mu_{R^2}(f_{\psi_t}(x)) = 0.9981$ with its variance of $\sigma^2_{R^2}(f_{\psi_t}(x)) = 5.423 \times 10^{-6}$ and $\mu_{R^2}(g_{\eta}(x)) = 0.9749$ with $\sigma^2_{R^2}(g_{\eta}(x)) = 1.8622 \times 10^{-4}$ indicating very
good fit for the data. The $R^2$ for $h_\theta(x)$ obtains lower accuracy due to outliers found in the measured data for $\theta$. Due to lower fit accuracy for $h_\theta(x)$ individual values of $R^2$ are given in Table I for inspection.

B. Evaluation of Wisent

We now present the results for the complete Wisent protocol, but we shall only proceed with evaluation of Wisent EX due to its generic nature. We will use the same experiment setup as in Section V-A, unless stated otherwise.

As in the case of evaluating BlockWrite performance we use tag-to-reader antenna distance $d$ as a parameter to evaluate Wisent. However, instead of WordCount, we take message payload size $S_p$ as the second parameter.

1) Wisent Performance Metrics: In Section V-A the experiments were executed with a single uninterrupted BlockWrite of a set duration, which in Wisent is equivalent to a single message. In Wisent, however, each of the previously used metrics also depends on the number of messages per second the RFID reader is able to process, i.e. the overhead discussed in Section III-C. Furthermore, a Wisent log file provides information on events that occurred between messages, rather than events which occurred within a predefined time. Therefore, we add $t$, the runtime of the transfer session, as a variable.

We introduce the following metrics: (i) the number of Wisent messages per second defined as $v = m_t/t$, where $m_t$ is the total amount of messages sent during the Wisent transfer session; (ii) number of success operations per message (SOPM) defined as $\psi_{sm} = n_s/m_t$, where $\psi_s = v\psi_{sm}$; (iii) the number of total operations per message defined as $\psi_{tm} = n_t/m_t$ with $\psi_t = v\psi_{sm}$; (iv) throughput defined as $\theta = 2S_p v$ (B/sec), (v) the resend rate defined as $p_r = \frac{m_r}{m_t} = \frac{m_r}{m_s}$ where $m_r$ and $m_s$ are the number of messages resent and sent, respectively, and (vi) $\eta$, whose definition is given in Section V-A.

2) Wisent Performance Results: We have experimented sending as many messages as possible and observed a value for $v \approx 3.8$ messages per second when using the Impinj R420 RFID reader and only half that amount with an Impinj R1000. This result is not affected by setting different values for OCV, which should change the size of the operation frame, and in turn lead to a smaller or bigger message frame. This has been confirmed by testing multiple values for OCV = \{5, 10, 15, 20, 25, 30\}. For OCV = \{5, 10\}, the host is observed occasionally not receiving an ACK in each message frame before the operation frame of that message ends and the message is deleted. For OCV = 20, the deletion of a message commanded by the host, explained in Section IV-B2, collides with the AccessSpecStopTrigger after executing 20 operations causing the reader to misbehave and cease the bitstream. Higher values for OCV causes the next message frame of each message to be flooded with NACKs and forces the resend of the message.
Only for the value $OCV = 15$, the bitstream remained operational. In all cases, however, the observed value for $v$ did not change and therefore we set $OCV$ to 15.

**Proposition:** $OCV \leq N_{\text{threshold}}$ should hold when selecting $N_{\text{threshold}}$ to increase the probability of acknowledged message.

**Proof:** Let $m_i$ and $m_{i+1}$ be messages with operation frames of length $f_o(m_i)$ and $f_o(m_{i+1})$, respectively. When $m_i$ is acknowledged, i.e. operation frame of $m_i$ has started, the message frame of $m_{i+1}$ starts, causing the remainder of the operation frame of $m_i$ to be NACKs in the message frame of $m_{i+1}$. Since $OCV$ acts as upper bound for $f_o(m_i)$ and $f_o(m_{i+1})$, the message frame of $m_{i+1}$ is now flooded with up to $f_o(m_i) - 1$ NACKs. $N_{\text{threshold}} < OCV$ would imply that the probability of $m_{i+1}$ getting acknowledged depends on $f_o(m_i)$ not reaching the upper bound.

For all our experiments, we set $N_{\text{threshold}}$ to 20 noting that proper investigation is required to get an optimal value.

As a first experiment with Wisent EX, now taken in a university office instead of laboratory, we transferred Intel Hex files without the throttling mechanism described in Section IV-D3, containing 5120 bytes of random data, which is around the same amount of bytes as an Intel Hex file of a WISP firmware generated by TI CCS. However, files generated by TI CCS have a maximum data length of 16 words per record that cannot be specified by the user. This forces the record to be split into messages of possibly different $S_p$ values other than the $S_p$ selected for the experiment. Therefore, we created Intel Hex files for our experiments ourselves in such a way that the records in each of the files hold the same number of words as the value of $S_p$ in the experiment. The results of each of these experiments with different set $S_p$ over multiple distances $d$ are shown in Figure 8. Assuming a rate of 3.8 messages/sec, the runtime of Wisent Basic would be over two times the amount of Wisent EX using $S_p$ of one word (Wisent Basic uses $S_p = 0.5$ and an additional two messages overhead for sending over the address field for each record). The speedup gained by Wisent EX this way only grows larger, the greater value of $S_p$ is used. However, the peculiarity in Figure 8 is the operation of Wisent EX at $d = 60$ cm, an unstable operating distance in Figure 7. Instead, this unstable operating distance is shifted to 80 cm, which can be explained by the presence of more metal objects found in the laboratory than in the office.

3) **Selection of Values for Throttling Parameters:** We now proceed to discuss the procedure of selecting values for throttling parameters in Wisent EX.

For the throttling mechanism, recall that $S_p, S_{p+1} \in T_t$ should hold. Let $T_t(S_p)$ and $T_t(S_{p+1})$ be the indices of $S_p$ and $S_{p+1}$ in $T_t$. Now, let $T_U$, $T_{DE}$ and $T_{DL}$ be denoted as $T_x = T_t(S_{p+1}) - T_t(S_p)$, i.e. the index difference between $S_{p+1}$ and $S_p$, where $T_U$ is used for throttling up, $T_{DL}$ for throttling down in cases
Fig. 8. Runtime, efficiency and total operations per message during a Wisent EX transfer as functions of $S_p$ over various distances.
TABLE II
SELECTED VALUES FOR WISENT EX THROTTLING PARAMETERS

| Parameter | T_U | T_DE | T_DL | R_{\text{max}} | M_{\text{threshold}} |
|-----------|-----|------|------|----------------|----------------------|
| Value     | 1   | -2   | -3   | 3              | 10                   |

Fig. 9. Flowchart of the proposed and implemented CRFID bootloader used for wireless reprogramming using Wisent. Compare this design with [11, Fig. 3] and its n + 1-way switch to determine which firmware program to run.

where timeouts are caused by NACKs due the reader losing sight of the CRFID (possibly a more severe case than e.g. NACKs due a mismatched EPC), and $T_{\text{DE}}$ for throttling down in cases where timeouts are caused by NACKs due any other reason. We propose the following condition that should hold when selecting values for $T_X$:

$$T_U < |T_{\text{DE}}| \leq |T_{\text{DL}}|, \quad |T_X| \in \mathbb{N}^+, T_{\text{DE}}, T_{\text{DL}} < 0. \quad (7)$$

Furthermore, for a message resent for the $R_{\text{max}}$-th time, its $S_p$ should be the minimum possible value, i.e. $S_p = T(1)$, even if before any resend of a message, i.e. $R_{\text{count}} = 0$, $S_p$ was at its maximum possible value, i.e. $S_p = S_t$. $R_{\text{max}}$ is then found by solving $R_{\text{count}}$ in $|T_t| - T_{\text{DE}}R_{\text{count}} = 1$.

The selected values we have chosen for all system parameters in Wisent EX can be found in Table II. We conjecture that the value of $M_{\text{threshold}}$ is related to $|T_t|$, since it decides the speed of which $S_p$ converges to a steady state during a set period of time where the communication channel is stable (i.e. the distance from CRFID to antenna is the same for that period). We note that further analysis should be done to reason about an optimal value for $M_{\text{threshold}}$. We nevertheless feel that a value of 10 supports the rest of values we have chosen for throttling.

C. Case Study: CRFID Wireless Reprogramming

As final evaluation, we demonstrate the ability to wirelessly reprogram the WISP by using Wisent EX with the selected parameter values in Section V-B3. For this, we created a bootloader that is manually programmed to the WISP and is not overwritten after the wireless programming, see Figure 9.
Fig. 10. Schematic overview of two experiments used to evaluate downstream data transfer with Wisent: (a) moving CRFID (A: antenna, W: WISP), (b) CRFID ex vivo placed between layers of meat (bacon) on RFID antenna.

| WISP Reprogrammed Firmwares | Firmware          | Size (bytes) | Runtime (sec) |
|-----------------------------|-------------------|--------------|---------------|
| WISP 5 (base)               | 5387              | 54.467       |
| WISPCam                     | 6442              | 65.097       |
| FM0 modulation              | 1199              | —            |
| Wisent functionality        | 528               | —            |

1 From static distance \(d = 20\) cm and with \(S_p = 16\).
2 Difference of sizes between base firmware with and without this functionality. Runtime omitted as patches were not made.

To initiate the wireless programming, the host sends a transfer initialization message as a Write command to enter programming mode. This command is recognized by the CRFID so that messages are handled correctly until the programming session is finished. When all data of the application is transferred, the CRC16 checksum over the whole application is sent to validate the firmware. If the checksum matches the calculated one on the CRFID, the programming session was successful and the bootloader will start the application.

| COMPARISON OF WISP 5 BASE FIRMWARE TRANSFER PERFORMANCE |
|-------------------------------------------------------|
| \(S_p\) | \(t\) (sec) | \(p_t\) | No. resends | No. transfers completed |
|--------|-------------|---------|-------------|------------------------|
| throttle | 248.448    | 0.0344  | 24.4        | 5/5                    |
| 1      | 810.000    | 0.0004  | 1.20        | 5/5                    |
| 2      | 462.585    | 0.0096  | 13.2        | 5/5                    |
| 3      | 403.974    | 0.0411  | 44.0        | 4/5                    |
| 4      | 351.899    | 0.0951  | 73.0        | 2/5                    |
| 6*     | —          | —       | —           | 0/5                    |

* \(t, p_t\) and no. resends were omitted as all transfers failed due to too many resends.

\(S_p = \{8, 16\}\) were omitted as they show the same result as for \(S_p = 6\).
1) **Experiment Setup and Results:** As experiments, we have adapted a measurement scenario to mimic movement of CRFID and its effect on channel quality using an in-house developed automaton for repeated indoor mobility [27]. For this the WISP is attached to nylon wires, which are then wound up/released by stepper motors (controlled by an Arduino) with a speed of approximately 0.1 m/s to move the WISP and change its distance to the antenna between 20 cm and 90 cm (i.e. between optimal distance and a distance where channel is unreliable) in a repeatable manner, see Figure 10(a). Results of these experiments using the constructed bootloader are listed in Table III and Table IV, which justifies the use of the throttling mechanism as proven in Section IV-D3. In comparison with the case of a set $S_p = 4$ the throttling mechanism cuts the transfer time of the base firmware down by approximately 100 seconds and even reduces the resend rate with almost three times while finishing all transfer attempts.

2) **Data Transfer Energy Consumption:** For result completeness and comparison to typical state-of-the-art WSN devices concerning the energy consumption used in downstream communication, we have used a Monsoon Power Monitor to measure the energy consumption of a Tmote Sky node storing 5387 bytes of data received from another node (WISP 5 base firmware length, see Table III). To represent Wisent EX messages in our experiment, the data was sent in chunks of 36 bytes with the X-MAC protocol present in Contiki OS. The measured energy consumption of the Tmote Sky is 256.35 mJ, while the WISP consumed a total of 81.70 mJ. This proves that despite Wisent not being designed with energy efficiency in mind, CRFID downstream transfer is at least three times more energy efficient than corresponding WSN downstream.

3) **Reprogramming Tissue-Embedded CRFID:** As an ultimate experiment, we demonstrate the ability to wirelessly reprogram a tissue-implanted CRFID. To emulate such a scenario we placed a cling film-wrapped WISP between 5 and 6 layers of meat (bacon) at the top and bottom of the WISP, respectively, placed on an antenna separated by a 6 cm paper box, see Fig. 10(b). This experiment followed similar ex vivo experiments emulating implantable sensor scenarios [4, Fig. 8]. We were able to successfully reprogram the WISP with complete RFID stack within 63.55 sec despite attenuation of the backscatter signals from the meat.

VI. LIMITATIONS AND FUTURE WORK

Wisent forms a baseline for experiments on downstream CRFID communication. Further required features are:

1) **Transfer to multiple tags at the same time:** although Wisent has been designed for transfers to a single CRFID tag, an extension for multiple tags is necessary which involves careful scheduling of
resources;
2) Security: to deploy reprogrammable CRFIDs, data transfer needs to be secured. Wisent as of now has no mechanism to prevent message spoofing. We argue that this is the most urgent feature missing in Wisent.

Other functionalities requiring consideration include the ability to resume a transfer after failure or addition of a data compression mechanism, which has a trade-off of performance versus computation power used by the CRFID.

VII. Conclusion

In this paper, we have designed and implemented a protocol, called Wisent, that allows to transfer bulk data from host to CRFID in a fast and robust manner. Wisent allows to store and verify data despite power interruptions at the CRFID thanks to the use of non-volatile FRAM memory and simple error verification mechanism. In addition, through introduction of large frame sizes (sent by the RFID reader), thanks to such ability of EPC C1G2 RFID communication protocol, and its length adaptations depending on the channel conditions, Wisent improves the throughput threefold in comparison to single word message size supported by the EPC C1G2 standard. Finally, implementation of Wisent allowed to introduce and experimentally verify the world’s first wirelessly reprogrammable (software defined) CRFID.

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