Optimal Data Transmission in Backscatter Communication for Passive Sensing Systems

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Abstract: Computational Radio Frequency IDentification (CRFID) is a device that integrates passive sensing and computing applications, which is powered by electromagnetic waves and read by the off-the-shelf Ultra High Frequency Radio Frequency IDentification (UHF RFID) readers. Traditional RFID only identifies the ID of the tag, and CRFID is different from traditional RFID. CRFID needs to transmit a large amount of sensing and computing data in the mobile sensing scene. However, the current Electronic Product Code, Class-1 Generation-2 (EPC C1G2) protocol mainly aims at the transmission of multi-tag and minor data. When a large amount of data need to be fed back, a more reliable communication mechanism must be used to ensure the efficiency of data exchange. The main strategy of this paper is to adjust the data frame length of the CRFID response dynamically to improve the efficiency and reliability of CRFID backscattering communication according to energy acquisition and channel complexity. This is done by constructing a dynamic data frame length model and optimizing the command set of the interface protocol. Then, according to the actual situation of the uplink, a dynamic data validation method is designed, which reduces the data transmission delay and the probability of retransmitting, and improves the throughput. The simulation results show that the proposed scheme is superior to the existing methods. Under different energy harvesting and channel conditions, the dynamic data frame length and verification method can approach the theoretical optimum.

Key words: uplink multi-data; frame length optimization; Computational Radio Frequency IDentification (CRFID); Cyclic Redundancy Check (CRC)

1 Introduction

In passive sensing networks, Computational Radio Frequency IDentification (CRFID) tags are different from traditional Radio Frequency IDentification (RFID) tags. CRFID can embed microprocessors and sensors into the RFID, so that they have the abilities of sensing and computing. Typical CRFID tags include Wireless Identification Sensing Platform (WISP)[1] developed by the University of Washington, and Moo[2] developed by the University of Michigan on the basis of WISP. CRFID obtains energy from the Radio Frequency (RF) signals to sense and identify environmental information, and transmits the sensing data to the reader by backscattering the RF signal of the reader[3]. Extensive research has been done on the applications of CRFID, including warehouse management[4], environment detection[5], passive awareness, and access control[6,7], among others. In view of these different application scenarios, CRFID needs to meet a common requirements to transmit a large amount of data efficiently.

The existing Electronic Product Code, Class-1 Generation-2 (EPC C1G2) communication protocol...
mainly identifies a small amount of data in a large number of tags. In EPC C1G2, the reader may receive short address messages of 16-bit Random Number (RN16) from one or more tags at any given timeslot. To enable RFID readers to read a significantly large population of tags within a small time interval, it is required to increase the underlying throughput by maximizing the percentage of timeslots in which the reader may receive RN16 messages correctly. Simultaneously, in order to detect or check possible errors after data transmission, EPC C1G2 introduces Cyclic Redundancy Check (CRC), which is a channel code technology that generates a short fixed-digit check code based on network data packets. The existing Gen2 protocol cannot be based on the actual conditions of the tag (in terms of throughput and energy capture), so it can not meet the need for data processing and transmission in terms of the communication rate. Figure 1 shows how the EPC protocol accesses a single tag, in which the shadow line part of the way is the continuous Carrier Wave (CW). In the C1G2 protocol, we know that according to the length of the command set, different data checking methods are used. At the same time, the data returned by tags can be used to dynamically adjust the data recovery length according to the reader’s command. Therefore, by dynamically adjusting the data transmission frame length and adjusting the check mode in real time according to the data frame length, the data transmission delay can be effectively reduced, the number of retransmissions can be reduced, and the overall throughput of the system can be improved.

This paper applies the CRFID to the mobile sensing scenarios. When the CRFID tag moves into the reader’s working range, the tag transmits the cached data to the reader through backscatter communication. The energy acquisition conditions and channel quality of CRFID change dynamically with movement. When the energy capturing conditions are poor, CRFID needs a long charging time to reach the working voltage, which can even lead to the discarding of data frames, that requires CRFID to recharge and retransmit data, so the rate of data exchange is reduced. The energy harvesting process is shown in Fig. 2. At present, this protocol is inefficient when a small number of CRFID tags need to transmit a large amount of cached data, and can not cope with dynamic changes in energy capture conditions and channel quality.

In this paper, we focus on the optimization of the design of CRFID for burst scenarios with high latency and low throughput. The dynamic adjustment of the data frame length is proposed according to channel quality. According to the length of data, the data validation mode is selected reasonably to reduce the data transmission delay.

The rest of this paper is organized as follows. Section 2 provides the background and motivations for the article. We describe the detailed design of the dynamic data frame adjustment and adaptive check code in Section 3. The experimental results are given in Section 4, followed by related work and discussion in Sections 5 and 6, respectively. Section 7 gives some conclusions.

2 Background and Motivation
CRFID works at the frequency band between 902 MHz and 928 MHz. High power RFID readers with 30 dBm transmission power energize and interrogate RFID devices, and collect data from them. The reader retrieve tag data through two types of command sets {ACK, EPC} and {Read, Data}. As shown in Table 1, the command sets of the reader sending...
to tag is \{PC+EPC+CRC\}. As shown in Table 2, the command sets of the tag replying to reader is \{0+data+RN16+CRC\}. Different from the \{ACK, EPC\} command in the identification procedure, the \{Read, Data\} command in the read procedure is tailored for bulk data transfer with variable lengths.

A natural way of reading bulk data from CRFIDs is using the \{Read, Data\} primitive of the C1G2 protocol. This approach naturally allows for C1G2 compatibility and can collect hundreds of bytes per message exchange in theory. Nevertheless, the actual success rate of data transfer substantially decreases as large data packets are requested from CRFIDs.

We investigated the response latency of CRFID requests for different data volumes, with the result displayed in Fig. 3. During the data transmission process, there is a strict time response mechanism. When the return command is too long, there is a risk of transmission interruption. The timing requirements of the C1G2 protocol are very strict, especially for lightweight CRFID. According to C1G2, the corresponding data should be strictly controlled in an appropriate range: data responses should be strictly within \(T_1 = \text{Max}(\text{RTcal}, 10/\text{BLF})\), where RTcal denotes the reader to RFID timing calibration duration, and BLF denotes the backscatter link frequency.

In order to ensure the integrity of data transmission, CRFID adds a 16-bit CRC to the data packet. A CRC is a kind of error detection coding widely used in digital communication and storage systems. CRC computational overhead increases linearly with data size. CRFIDs need to compute CRCs and append them to data packets before responding to readers. CRFIDs can not meet the response period required by commercial standards in practice. The fundamental reason is that the time response requirement, which is very close to the commercial standard C1G2 protocol, does not meet the dynamic working conditions of CRFIDs.

The C1G2 protocol specifies that the encoding side of the tag uses FM0 or Miller coding\(^9\). According to the different quality of the communication link, the reader changes the \(P\) value in the query command to control the coding mode of the tag\(^10\). By studying the advantages and disadvantages of the two codes, we can dynamically select the data coding method according to the different channel conditions. Therefore we mainly aim at the above two problems to optimize the design.

FM0 is suitable for good link quality. For example, in a simple communication environment, there is one reader and one tag, with small signal interference and rich spectrum resources. Miller coding can reduce the data rate, improve anti-interference ability, and achieve high efficiency of spectrum resources (for Miller coding specific features please refer to WISP, which uses Miller-4 encoding). The data rate of the tag to reader for different \(P\) values are shown in Table 3, where LF represents link frequency.

Our design for the dynamic frame adjustment strategy has many benefits. One is the combination of different sizes of data and throughput of the actual situation using real-time dynamic adjustment, so that the real-time channel can be used to determine the situation of data transmission. The strategy analyzes the energy condition and channel quality of the WISP system to obtain the best frame length for the specific energy storage of the data transmission. This strategy has greatly optimized the data uplink transmission. When we get the optimal frame length for different energies, we take into account the reliability of data transmission and propose a method to dynamically adjust the CRC check. This ensures that the verification is correct and makes this method safe for WISP label energy consumption while reducing the large number of delays generated by the CRC calculation.

### 3 System Design

As mentioned in the previous section, CRFID works in a mobile scenario. Energy capture and the dynamic environment will directly affect the working state of CRFID, which is more sensitive than traditional

| \(P\) | Modulation type | Data rate |
|-----|----------------|-----------|
| 1   | FM0            | LF        |
| 2   | Miller         | LF/2      |
| 3   | Miller         | LF/4      |
| 4   | Miller         | LF/8      |

![Fig. 3 Long delay causes communication interruption.](image-url)
wireless communication. Nowadays, many near field communications are used for the wireless transmission of data in order to achieve higher transmission rate. Due to the mobility and variability of the WISP communication nodes, the environment of the communication link may be constantly changing\cite{11,12}. Noise interference caused by changes in frequency and intensity can be quite severe. In the IEEE802.11 adhoc network used by the ISM band, there are many other facilities in the network\cite{13}, if the communication link quality is unstable, the noise on the communication interference is very severe. It is difficult to avoid and detect signal conflicts, and the conflict will reduce the communication efficiency. To improve the system performance, we introduce the variable frame to reduce the conflict.

For the fixed frame length will lead to the inefficient communication, it is not advisable to use it in the passive network. In harsh communication link conditions, the use of shorter frames is an easy way to avoid interference, which is a good way to reduce the probability of conflict, and make full use of the channel’s communication capabilities\cite{14}. In better communication link conditions, the use of longer frames is preferable, such that each transmission contains more information to achieve the full use of the channel. In harsh conditions, the use of long frames gives a large probability of failure, such that the long-term efficiency is not as good as the use of short frames. Using short frames under good conditions generates useless overhead and wastes the communication capacity of the channel. Therefore, using a variable length frame to communicate can maximize the utilization of a passive sensing link. To improve the communication quality and working efficiency of the system, we designed a new running logic of the reader and the tag, as shown Fig. 4. In our design, the reader is powered on and initialized, and the tag needs to be activated by the reader, then the communication is established, and the status of the data transmission can be adjusted in real-time through the effective throughput. The design logic of the tag side and reader side is shown in Algorithms 1 and 2, respectively. In Algorithm 2, \(l\) is the buffered data, \(l_{\text{init}}\) is the initial buffered data, \(F\) is the number of errored frames, and \(V\) is the number of correctly accepted data frames. Set the above variables as zero. \(A\) is the number of data frames to be sent. \(\omega\) represents the data check bit frame length (frame tail

\[ \text{Algorithm 1 WISP sensor's running logic} \]

1. \textbf{while} the buffer cache data \(= 0\), do
2. WISP tracks the current \(U_{\text{max}}\) and \(\tau\);
3. \textbf{if} receive the command \(=\{\text{Query}\}\) then \(\text{Reply} = \{\text{RN16}\}\);\n4. \textbf{end}\n5. \textbf{if} receive the command \(=\{\text{Query Rep}\}\)\n6. \(\text{Reply} = \{\text{RN16 & delete the transmitted data in the buffer}\}\);\n7. \textbf{end}\n8. \textbf{if} receive the command \(=\{\text{ACK}\}\) then
9. \textbf{if} total transmission count \(\leq \text{limit} K\) then
10. scratch \(l\) data from the buffer, form a frame and transmit it to the reader, keep the data in the same buffer;
11. \textbf{end}\n12. \textbf{end}\n13. \textbf{else}\n14. discard the current frame and delete the corresponding register, encode the data as \(N + M\) frames, and its structure is determined by the ACK at present.
15. \textbf{end}\n16. turn off the radio and sleep for a period of \(t\), where \(t\) is the minimum value computed by Eq. (4)
17. \textbf{end}\n18. \textbf{end}

\[ \text{Algorithm 2 Reader's running logic} \]

1. set \(l = l_{\text{init}} = 0\), \(F = 0\)
2. WISP sends the Query command
3. \textbf{if} receive the RN16 from the tag \textbf{then}
4. send the ACK with the same RN16 and indicate the payload length \(l\) to the tag. For the first time, set \(N\) and \(M\) to the default values
5. \textbf{end}\n6. \textbf{if} receive the frame from the tag \textbf{then}
7. \textbf{if} the frame is checked to be correct \textbf{then}
8. \(A = A + l\), send the QueryRep
9. \textbf{end}\n10. \textbf{if} the window with \(\omega\) is full \textbf{then}
11. \(t_p = V/\Delta t\), where \(\Delta t\) is the end time of the window
12. \textbf{if} \(t_p > t_p(1+\delta)\) \& \(l < l_{\text{max}}\) then \(l = l + \Delta l\)
13. \textbf{end}\n14. \textbf{else if} \(t_p < t_p(1-\delta)\) \& \(l > l_{\text{max}}\) then \(l = l - \Delta l\)
15. \textbf{end}\n16. \(t_p = t_p',\) empty the window
17. \textbf{end}\n18. \textbf{if} the frame is checked to be erroneous \textbf{then}
19. send ACK with the same RN16 and indicate the payload length \(l\) to the tag
20. \textbf{end}

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![Fig. 4 Reader's running logic.](image-url)
length). \( t_p \) is the effective throughput, and \( t'_p \) is the effective throughput of the previous round.

### 3.1 Dynamic frame length strategy in backscatter link

CRFID’s duty cycle is relative to storage capacitor charging and discharging process. After a period of sleep and the dormant process to obtain the RF energy from the reader, the capacitor begins to charge, then the voltage begins to rise\(^{[15]}\), when it reaches the working voltage, CRFID goes into work mode and starts sending data to the reader. As one version of CRFID, for example, WISP, with the MSP430’s operating voltage of 1.8 V, when the voltage rises to 2.0 V, it can wake up the WISP sensor to send data. The charging voltage of the WISP node is in the following:

\[
U(t) = U_0 e^{-t/\tau} + U_{\text{max}} (1 - e^{-t/\tau}) \tag{1}
\]

where \( U_0 \) is the voltage at the beginning of the charge, \( \tau \) is the time constant of the RC circuit, and \( U_{\text{max}} \) is the maximum charge voltage that the capacitor can achieve under the current energy capture conditions. With a change of environmental conditions, the maximum charge voltage that the capacitor can achieve will change. When the energy capture conditions are poor, \( U_{\text{max}} \) reduces and \( \tau \) increases. This means the WISP tag requires a longer charging time to reach the radio of operating voltage. In order to adapt to different energy capture conditions, this paper proposes a dynamic selection of frame length and charging time for WISP tags. Another advantage of dynamically selecting the frame length is the ability to adapt to the changing channel quality. By combining the optimized frame length, coding redundancy, and charging time, the throughput of the backscatter communication is improved.

At first, we need the expression of the effective throughput for specific energy capture conditions and channel conditions. When the charging time is \( t \), the amount of energy WISP can capture is

\[
E(t) = \frac{1}{2} C(U_{(t)}^2 - U_{\text{min}}^2) \tag{2}
\]

where \( C \) represents the size of the charge capacitance in WISP and \( U_{\text{min}} \) represents the minimum operating voltage of the WISP. Here we assume that the average energy consumed by each bit of data that WISP tag receives or sends is \( E_{\text{bit}} \). We can then calculate the energy WISP needs to send a frame in each duty cycle,

\[
E_{\text{frame}} = E_{\text{bit}} \times (\alpha + l + \omega) \tag{3}
\]

where \( \alpha \) represents the frame header length and \( l \) represents the length of the data frame.

We are here to meet one of the conditions that is limited by the capture of energy,

\[
E_{(t_k)} \geq \chi_k E_{\text{frame}} \tag{4}
\]

where \( E_{(t_k)} \) represents the energy captured by the tag node when charging time of the \( k \)-th cycle is \( t \), \( \chi_k \) indicates the number of data frames transmitted by WISP during the \( k \)-th duty cycle. According to Eq. (4), we can then conclude that the number of data frames sent by WISP in the \( k \)-th duty cycle satisfies the following condition:

\[
\chi_k \leq \min \left\lfloor \frac{E_{(t_k)}}{E_{\text{frame}}} \right\rfloor N + C - \sum_{i=1}^{k-1} \chi_i \right\rfloor \tag{5}
\]

where \( \lfloor \cdot \rfloor \) is rounded down, \( \sum_{i=1}^{k-1} \chi_i \) indicates the total number of data frames transmitted before the \( k - 1 \) duty cycles. Substituting Eqs. (2) and (3) into Eq. (4), while letting \( U_0 = U_{\text{min}} \) in Eq. (2), we can get the \( k \)-th duty cycle of the charging time, satisfying the following inequality:

\[
t_k \geq -\tau \ln \frac{\sqrt{2\chi_k E_{\text{bit}}(\alpha + l + \omega)C + U_{\text{max}}^2 - U_{\text{min}}^2}}{U_{\text{min}} - U_{\text{max}}} \tag{6}
\]

According to Eq. (6), we can send each frame of data, the charging time is described in the following formula:

\[
\overline{t} = \frac{t_k}{\chi_k} \tag{7}
\]

The main idea of dynamic frame length adjustment control is to adjust the frame length and coding redundancy according to the throughput measurement of the reader at runtime and to control the charging time, thus improving the throughput of the data. The specific ideas are as follows. The first WISP cycle tracks the storage capacitor voltage, gives access to dynamic \( U_{\text{max}} \) and \( \tau \) values. When WISP moves to the reader and has data to be sent to the reader, \( N \) source data frames of length \( l \) are extracted from the cache, encoded as \( N + M \) frames, where \( M \) is the number of redundant frames, the initial frame length is set to 32 bits. When a round of data transmission is completed, the reader records the time taken and the effective throughput during this time, and compares the current throughput with the previous round.

If the current throughput is higher than that of the previous round, the return ACK informs the tags to increase the transmit frame length; otherwise, the transmit frame length is reduced, the unit of the frame length is increased or decreased by 16 bits each time. In
order to avoid frequent changes in the frame length, we introduce an adjustment parameter, if the increasing or decreasing proportion of the throughput does not exceed this threshold, the frame length is not changed\[16\]. At the same time, after receiving the reader’s specified frame length, the WISPI\[17\] tag selects the number of frames transmitted in the current working period according to the current energy capture condition, enters the sleep charging state after sending, waits for the next work cycle to transmit the data. This continues until the current round of data frames are all finished, or until the reader sends a QueryRep frame. After a round of transmission, if the transmission fails to send the number of redundant frames \(M\), the reader checks the current actual number of redundant frames according to Eq. (8) on the next round,

\[
M_{\text{next}} = \left[ (1 - \gamma) \times M_{\text{avg}} + \gamma \times M_{\text{cur}} + M_{\text{min}} \right],
\]

\[
\gamma \in (0, 1), M_{\text{next}} \in (M_{\text{min}}, M_{\text{max}})
\]

where \(M_{\text{avg}}\) indicates the average number of redundant frames sent historically, \(M_{\text{cur}}\) indicates the number of redundant frames sent in this round, \(M_{\text{min}}\) and \(M_{\text{max}}\) are the minimum and maximum number of redundant frames, respectively, and the weight coefficient \(\gamma\) indicates rounding up.

### 3.2 New CRC algorithm design

The simulation of the CRC check capability is controlled by the program. In the program, the control model runs 500 times. After each simulation model running, it is checked for an error code. We look at whether an error has occurred, using \(e\) and \(e_1\) to represent the actual number of errors of the final statistics and the number of errors of CRC’s detection, respectively. In this way, we can count the error rate of the CRC check, which is calculated as follows:

\[
\eta = \frac{e_1}{e} \times 100\%
\]

If the reader requests a fixed-length response data from WISP, we use different redundant CRC check codes to analyze it. The results obtained by this method are shown in Table 4.

| Check digit | Check errors | Total errors | Error rate (%) |
|-------------|--------------|--------------|----------------|
| CRC-5       | 395          | 496          | 80             |
| CRC-8       | 496          | 496          | 100            |
| CRC-16      | 496          | 496          | 100            |

At present, the dynamic data frame length used in WISP tags is not a new topic in academia, but there are some gaps in the use of redundant check bits for different data frame lengths. The resulting of large time interval manifests an excessively long response latency, which will lead directly to the failure of data transmission.

The C1G2 protocol for RFID tags is designed to inventory large tag populations over a number of communication rounds. To realize this protocol, an RFID must traverse a simple state machine and respond appropriately to a set of reader commands.

Following the identification procedure, the RFID reader further requests for more data in the read procedure. The RFID reader establishes a handshake by \{ReqRN, Handle\}. Similar to \{Query, RN16\} handshake in the identification procedure, \{ReqRN, Handle\} is short, serving the collision arbitration purpose. The reader then acknowledges the 16-bit handle and requests a large amount of data. According to the C1G2 standard, the reader is able to collect up to 510 bytes per \{Read,
Data exchange. Different from \{ACK, EPC\}, which is primitive in the identification procedure, the \{Read, Data\} primitive in the read procedure is tailored for bulk data transfer with variable lengths. But in the previous code test, when more than 8 bytes of data are requested in the read procedure, the success rates suddenly drop to zero even within a small interrogation range.

The data frame format used in this paper is similar to that in the EPC Gen2 protocol. The length of the data load in the EPC Gen2 protocol is defined by the EPC length field in the protocol control field, in the range of 16–496 bits, and is an integer multiple of 16 bits, in this case, the number of bits is incremented or decremented by 8 bits each time. Considering that the current device only supports 96 bits, the maximum is 01100, for EPC Gen2, the ACK frame format specified by the protocol consists of 2 bits command and 16 bits random number bits. However, in the algorithm presented in this paper, the frame length and the number of redundant frames need to be adjusted according to the channel condition and the capture condition, which is fed back to the WISP tag by the reader through the ACK frame. Therefore, it involves two additional 5 bits command in the ACK, stating the frame length of the next round and the number of redundant frames in the ACK frame format.

The combination RN16+CRC16 is the most commonly used response of the tag in the uplink, but we have already explained that the CRC-16 verification for a data frame whose length of less than 256 bits involves a lot of energy waste. When the tag returns RN16, CRC-5 is sufficient to complete the inspection task, which saves energy and reduces MCU computing time. For the dynamic EPC data frame, the different checksum bits are determined according to the different frame lengths. Here, assuming that $x$ is the length (bit) of the EPC data to be transmitted, the throughput of the channel and the power of the storage capacitor are determined by the data frame length. The following formula determines the checksum bits for calibrating the frame length of the next round of transmission:

$$
\text{CRC-X} = \begin{cases} 
\text{CRC-5,} & x < 32; \\
\text{CRC-8,} & 32 \leq x < 256; \\
\text{CRC-16,} & 256 \leq x < 6400
\end{cases}
$$

(10)

The key to the CRC check is to generate a cyclic redundancy code based on the generator polynomial and the information to be sent. According to the EPC Gen2 protocol, the cyclic redundancy code is suitable for the small memory space (the code takes up less memory space), but the whole process takes a long time and the real-time performance is poor. The reader and tag have two CRC checks: CRC-5 and CRC-16. For CRC-5, this paper presents a byte-by-table method. Since the amount of data exchanged between the reader and the tag is not an integer multiple of the byte, it is not sufficient to find the CRC in bytes. We use a look-up table to solve this problem, with the basic idea that CRC-5 will be translated into CRC-8, then the corresponding generation polynomial is found; according to the generated polynomial, cycle redundancy table is generated, and then through the look-up table, CRC-8 is found and finally converted back to CRC-5.

In the beginning, the principle of converting CRC-5 to CRC-8 is shown in Fig. 5. Assuming that $A(x)$ is a polynomial of the information symbol to be transmitted by the UHF reader and $G(x)$ is a polynomial of CRC-5 (short form 0x09), in the formula for finding the cyclic redundancy code,

$$
\frac{2^{16} A(x)}{G_5(x)} = \frac{2^{16} A(x)x^3}{G_5(x)x^3}
$$

(11)

let $\tilde{A}(x) = A(x)x^3$ and $G_8(x) = G_5(x)x^3 = x^8 + x^6 + x^3$, then Eq. (11) can be converted to

$$
\frac{2^{16} A(x)}{G_5(x)} = \frac{2^{16} \tilde{A}(x)}{G_8(x)}
$$

(12)

$$
\tilde{A}(x) = 2^8 \tilde{A}_n(x) + 2^{8(n-1)} \tilde{A}_{n-1}(x) + \cdots + 2^0 \tilde{A}_0
$$

(13)

According to the principle of the look-up table formula we can deduce Eq. (13),
\[
\frac{2^8 A'(x)}{G_8(x)} = 2^{8n} Q_n(x) + 2^{8(n-1)} \times \\
\frac{2^8 [R_n(x) + A'_{n-1}(x)]}{G_8(x)} + \cdots + 2^{9} \frac{2^{8} A'(x)}{G_8(x)}
\]

(14)

where \(Q_n(x)\) and \(R_n(x)\) are complete and residual functions of CRC-8 for \(A(x)\), respectively. From Eq. (14), the redundant period is the XOR operation of the period of the redundant code and the redundant code, and then the CRC-8 cycle redundancy table is generated, from which we can get the generated polynomial of CRC-8. Generator polynomial should be written to 0x48 with the abbreviated version 0x09 of the CRC-5, which is written as 0x80 of the CRC-8.

4 Implementation and Evaluation

4.1 Implementation and experiment setting

(1) RFID reader. In this test, we use the Imping R420 Reader, which has a four-transceiver antenna interface, dedicated for the Impinj reader antenna optimized high-performance unipolar antenna port (RP TNC). The basic requirements for this lab setup can be accomplished, and the commercial reader can operate in a variety of configurations, such as single read, continuous monitoring, and so on. Implementing the reader side data transfer protocol is time-consuming, and is compatible with C1G2, so we can think that the reader can be set to meet the overall requirements of the experiment[19]. To meet the high dynamic range processing capability needs, we also used another reader USRP N210 to meet the different experiment requirements. The experimental settings are shown in Fig. 6.

(2) WISP tags. The design is based on WISP5.0 hardware and firmware. The WISP5.0 is equipped with an MSP430 R5969 series microcontroller, it supports fast read and write commands, and FRAM non-volatile memory for ultra-low energy data storage and retrieval. The WISP firmware program, using C and assembly code to complete, has been partially implemented to C1G2 standard. What we mainly do is adding the three modules to the WISP firmware module: the CRC calculation module, the scheduling module, and the data transfer module. In particular, we use the parallel data validation algorithm, which roughly saves 70% of the CRC calculation time, greatly reduces the data transmission delay.

(3) Experiment setup. The Alien ALR-9900+ reader uses one ALR-8696-C circular polarized antenna with a gain of 8.5 dB for transmission, as well as reception. The RFID devices are attached to a poster panel parallel to the antenna and 1 m away with line-of-sight paths to the reader. We vary the power output from 18 dBm to 30 dBm to study the data transfer performance with different power conditions. Our experiments take use of the equivalent distance in the free-space[20].

4.2 Performance of the strategy

For this design strategy we assume that there are 8000 bits of cached data in the WISP tag that need to be sent to the reader. The simulation results show that, compared with the fixed 96-bit frame length strategy and EPC Gen2 to obtain the theoretical optimal solution, the throughput performance, corresponding frame length, and redundant frame number are more reasonable.

Figure 7 shows that the throughput of the three schemes increases with increasing Signal to Noise Ratio (SNR) under the energy capture conditions of \(U_{\text{max}} = 5\) V and \(r = 1\). As the SNR increases, throughput gradually increases, and finally tends to be stable. The theoretical value of the throughput obtained by the exhaustive method in Fig. 7 is greater than that

![Fig. 6 Experiment settings.](image-url)

![Fig. 7 Throughput performance of the three schemes under the condition \(U_{\text{max}} = 5\) V and \(r = 1\).](image-url)
proposed in this paper and the fixed frame length scheme, but the theoretical value depends on accurate channel quality and charging condition estimation. In practice, estimating the channel quality requires additional communication overhead. The strategy proposed in this paper does not need to estimate the channel quality. The throughput is close to the theoretical optimal value, and much higher than that of the fixed 96-bit frame length strategy. Because of the limited communication distance of the passive sensing tags, our experimental results cannot be combined with the influential factor of communication distance. We have calculated the throughputs at different communication distances. In terms of data transmission time delay, compared to the fixed frame length strategy, we find that the dynamic strategy is very feasible, because we can get data through the dynamic frame length. Obviously, our algorithm has better throughput and less transmission delay. The communication energy consumption and optimal frame length under different values of the ratio of energy per bit to noise power density (E/N) are shown in Fig. 8.

Figure 9 shows the change of throughput performance with the increase of SNR under different energy capture conditions. Different energy capture conditions are represented by changing the maximum charging voltage. With the improvement of energy capture conditions, throughput also increases, because when the energy capture conditions are better, tags exchange more data information in a working cycle. Ultimately, throughput is increased. Figure 10 shows multi-tag throughput.

5 Related Work

For CRFID platforms, backscatter radio is designed both to provide power and enable to communicate. Aiming at the inefficiency of the EPC C1G2 protocol in transmitting large amount of cached data in mobile sensing scenarios, some improvements have been proposed in the literatures. In Ref. [21], the link layer protocol “Blink” is designed. The channel monitoring algorithm is designed to optimize the throughput by adaptively adjusting the data transmission rate and selecting the channel by estimating the packet loss rate.
and signal strength. In Ref. [22], the Flit protocol uses burst transmission to improve channel utilization, and a coordination algorithm to reduce the conflict among CRFIDs, which improves the throughput and energy efficiency compared to EPC Gen2.

In fact, Blink and Flit can be used in conjunction with the proposed program to further improve throughput. Similar to the research conducted in this paper, Ref. [23] devised a special communication protocol that cut the data frame into very small data units to accommodate environments in which low energy use is paramount. However, this work does not take into account the situation where the channel quality is poor and bit errors and retransmission occur[24].

6 Limitations and Future Work

The dynamic data frame strategy used in this paper is a baseline for experiments on uplink CRFID communication. Further required features are as follows.

(1) A faster and lower-power data validation method. Although the method used to dynamically adjust the redundant bit parity in this paper is a great improvement, it is still possible to make improvements in clock utilization by, for example, using parallel data processing, or improving the CRC check algorithm. In cases where storage space is allowed, the calculation of the MCU can be reduced using the preset CRC check.

(2) Security of data transfer. To deploy data transmission in the backscatter links, the data transfer needs to be secured. The proposed strategy as of now has no mechanism to prevent message spoofing. We argue that this is the most urgent feature missing in WISP. Other functionalities required consideration, including the ability to resume a transfer after failure, and the addition of a data compression mechanism, which involves a trade-off of performance versus the computation power used by the CRFID[25, 26].

(3) Downlink communication. We know that at the WISP label, there is much research on the reading of tag data, but there are still many technical problems for downlink data transmission, such as networking and data broadcasting, even at low power. Storage is also a very difficult problem to solve. Future research extends to downlink issues, such as wireless reprogramming and wireless program switching issues.

7 Conclusion

In this paper, we have designed and implemented a new protocol that allows for the transfer of bulk data from CFRID to host in a fast and robust manner. According to the reader-side throughput and tag-side energy measurement feedback, the proposed method adjusts the data transmission frame length and coding redundancy, thereby enhancing the throughput. The experiment results verify that the scheme proposed in this paper is superior to the EPC Gen2 protocol’s fixed frame length and fixed data verification in terms of throughput performance, and is close to the theoretical optimal value. The passive sensing network in our research can operate in the backscatter communication mode, adapt to the dynamic changes of energy capture and channel environment, and promote its applications in the field of mobile sensing. The new CRC algorithm can effectively improve the efficiency of cyclic redundancy checks in the UHF RFID system. An increase in the amount of data transmitted improves the efficiency of the method, makes it more suitable for embedded real-time systems.

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