Analysis and Improvement of the Lightweight Mutual Authentication Protocol under EPC C-1 G-2 Standard

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Abstract

Radio Frequency Identification (RFID) technology is a promising technology. It uses radio waves to identify objects. Through automatic and real-time data acquisition, this technology can give a great benefit to various industries by improving the efficiency of their operations. However, this ubiquitous technology has inherited problems in security and privacy. EPC Class 1 Generation 2 has served as the most popular standard for passive RFID tags. To improve the security of this standard, several protocols have been proposed compliant to this standard. In this paper we analyze the revised Yeh et al.'s (2010) protocol by Habibi et al.'s (2011) which is conforming to EPC-C1 G2 standard and is one of the most recent proposed protocols in this field. We discuss several drawbacks of this protocol, then we present our enhanced protocol which the security analysis showed that it can improve the security and privacy of RFID systems.

Keywords: RFID, EPC, Mutual Authentication, Security, Privacy, Adversary

1. Introduction

Radio Frequency Identification, abbreviated “RFID” basically provides a means to identify objects having RFID tags attached. Fundamentally, RFID tags provide the same functionality as barcodes but usually have a globally unique identifier. Using RFID, the identification is performed electromagnetically. Thus, there is, in contrast to barcodes, no line-of-sight necessary, and the identification can also be performed in contactless way. RFID also has the advantage that bulk reading is possible and that it is not susceptible to dust, dirt, or vibration like barcodes. Because of these characteristics, RFID is envisioned to be a convenient replacement for optical barcodes in the future [1]. There are several interconnected standards for RFID systems. Among them, ISO and EPC global have played the main role. In 2004 [2,3], the Electronic Product Code Class-1 Generation-2 specification (EPC-C1 G2 in short) was announced by EPC Global which also has been ratified by ISO [4] and published as an amendment to ISO/IEC18000-6. This standard is an important milestone for the standardization of low-cost RFID tags. However, the later security analysis that carried out on the EPC-C1 G2 specification have demonstrated important security flaws in this standard [5,6]. This is motivated researchers to try to propose EPC-compliant schemes, trying to correct the weaknesses and improve its security level, analyze the security of EPC-compliant schemes, or improve the vulnerable schemes [7,8,9,10,11,12,13,14]. Among them, one of the most recent proposals that following this approach is an improvement to the Yeh et al.’s protocol [14] proposed by Habibi et al. [12], which is the main concern of this paper. Habibi et al. [12] have analyzed the security of Yeh et al.’s protocol and proposed an improved protocol as a treatment for Yeh et al.’s protocol. However, other researches [7,11] have demonstrate that they were not success in their attempt and the proposed protocol has security and privacy problems. In this paper we proposed an enhanced protocol that improving cited problems. The security analysis showed that the proposed protocol can improve the security and privacy of RFID systems. Also, it can be applied in low-cost RFID environments requiring a high level of security.
2. Review of Habibi et al.’s protocol

This section reviews Habibi et al.’s protocol [11].

Notations used in this paper are defined as follows:

<table>
<thead>
<tr>
<th>Notation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPCs</td>
<td>The 96 bits of EPC code are divided into six 16-bit blocks, and then the six blocks are XORed to get EPCs.</td>
</tr>
<tr>
<td>DATA</td>
<td>The corresponding record for the tag kept in the database.</td>
</tr>
<tr>
<td>K</td>
<td>The key in the record of the database is found which key in the database is found.</td>
</tr>
<tr>
<td>RID</td>
<td>The reader identification number.</td>
</tr>
<tr>
<td>C</td>
<td>The database index stored in the tag to find the corresponding record in the database.</td>
</tr>
<tr>
<td>P</td>
<td>The access key stored in the tag for the tag to authenticate the database at the (i+1)th authentication phase.</td>
</tr>
<tr>
<td>K_{old}</td>
<td>The old authentication key stored in the database.</td>
</tr>
<tr>
<td>K_{new}</td>
<td>The new authentication key stored in the database.</td>
</tr>
<tr>
<td>P_{old}</td>
<td>The old access key stored in the database.</td>
</tr>
<tr>
<td>P_{new}</td>
<td>The new access key stored in the database.</td>
</tr>
<tr>
<td>C_{old}</td>
<td>The old database index stored in the database.</td>
</tr>
<tr>
<td>C_{new}</td>
<td>The new database index stored in the database.</td>
</tr>
<tr>
<td>X</td>
<td>The value kept as either new or old to show which key in the record of the database is found matched with the one of the tag.</td>
</tr>
<tr>
<td>A→B</td>
<td>A forwards a message to B.</td>
</tr>
<tr>
<td>A⊕B</td>
<td>Message A is XORed with message B.</td>
</tr>
<tr>
<td>RID</td>
<td>The reader identification number.</td>
</tr>
<tr>
<td>H(.)</td>
<td>Hash function.</td>
</tr>
</tbody>
</table>

The information kept within respective devices:

Tag: (K, P, C, EPCs)

Reader: RID

Database: (K_{old}, P_{old}, C_{old}, K_{new}, P_{new}, C_{new}, RID, EPCs, DATA)

Habibi et al.’s protocol consists of two phases: the initialization phase, and the (i+1)th authentication phase.

2.1. Initialization phase

The manufacturer generates random values for K0, P0 and C0 respectively, and sets the values for the record in the tag (K_{old}=K_{0}, P_{old}=P_{0}, C_{old}=C_{0}) and the corresponding record in the database (K_{old}=K_{new}=K_{0}, P_{old}=P_{new}=P_{0}, C_{old}=C_{new}=0).

2.2. The (i+1)th authentication phase

The detailed steps of the authentication phase of Habibi et al.’s protocol are presented as follows:

1) The reader R generates a random number N_R and sends it to the tag T.
2) T receives N_R, generates a random number N_T, computes M1, D, E and sends M1, D, E to R, where M1 = PRNG(EPC_S ⊕ N_R ⊕ N_T) ⊕ K and D = N_T ⊕ K, and E = N_T ⊕ PRNG(C_i ⊕ K_i).
3) When R receives the message, it computes V = h(RID ⊕ N_R) and forwards M1, D, C_i ⊕ E, N_R, V to the back-end server S.
4) After S receiving M1, D, C_i ⊕ E, N_R, and V, it proceeds as follows.
   - For each RID stored in the database, it computes h(RID ⊕ N_R) and compares it with the received V to verify R legitimacy.
   - If C_i = 0, which means that it is the first access to the database, it proceeds as follows, iteratively:
     a) Picks up an entry (K_{old}, P_{old}, C_{old}, K_{new}, P_{new}, C_{new}, RID, EPCs, DATA) stored in database.
     b) Verifies whether M1 ⊕ K_{old} = PRNG(EPC_S ⊕ N_R ⊕ D ⊕ K_{old}) or M1 ⊕ K_{new} = PRNG(EPC_S ⊕ N_R ⊕ D ⊕ K_{new}), and marks X as old or new provided that the verification process is satisfied.
   - Otherwise, S uses C_i as an index to find the corresponding record in the database and verify whether PRNG(EPC_S ⊕ N_R ⊕ D ⊕ K_{X}) ⊕ K_{X} = M1. If “No” the protocol aborts.
   - If C_i ⊕ PRNG(C_i ⊕ K_{X}) = E. If “No” the protocol aborts.
   - Computes M2 and Info and forwards them to R, where M2 = PRNG(EPC_S ⊕ N_T ⊕ D ⊕ K_{X}) ⊕ K_{X} = M1. If C_i ⊕ PRNG(C_i ⊕ K_{X}) = E. If “No” the protocol aborts.
   - Computes M2 and Info and forwards them to R, where M2 = PRNG(EPC_S ⊕ N_T ⊕ D ⊕ K_{X}) ⊕ K_{X} = M1. If C_i ⊕ PRNG(C_i ⊕ K_{X}) = E. If “No” the protocol aborts.
5) Once R receives the message, it extracts DATA as Info and forwards M2 to T.
6) When T receives the message, it verifies whether PRNG(EPCs ⊕ N_T) = M2 ⊕ P.
If “No” the protocol aborts. Else T authenticates S and updates the contents kept inside as K_{old} \leftarrow PRNG(K), P_{old} \leftarrow PRNG(P_i), C_{old} \leftarrow PRNG(N_i \oplus N_R).

3. Weaknesses of Habibi et al.’s protocol

3.1. Secret Information Disclosure Attack

Castro et al. [7] present an efficient and passive attack that retrieves any Secret Information of the tag include EPCs, K, and P. The adversary acts as follows:

1. Eavesdrops one session of protocol and stores all transferred messages include: N_E, C_i, M_1 = PRNG(EPC_i \oplus N_R \oplus N_T) \oplus K, D = N_T \oplus K, E = N_T \oplus PRNG(C_i \oplus K), M_2 = PRNG(EPC_i \oplus N_T) \oplus P_X.

2. Phase1 (Learning): The adversary eavesdrops one successful run of the protocol and stores the messages exchanged between the reader and the legitimate tag including N_R, M_1, D, C_i and E. At the end of this phase the records linked to this tag in the back-end database include (K_{old}, P_{old}, C_{old}, K_{new}, P_{new}, C_{new}, RID, EPCs, DATA) and the tag record includes (K_{new}, P_{new}, C_{new}, EPSs), where: K_{new} = PRNG(K_{old}), P_{new} = PRNG(P_{old}), C_{new} = PRNG(N_i \oplus N_R), M_1 = PRNG(EPCs \oplus N_R \oplus N_T) \oplus K_{old}, D = N_T \oplus K_{old} and E = N_T \oplus PRNG(K_{old} \oplus K_{old}).

3.2. Tag Impersonation Attack

Phase 2 (Impersonation): To impersonate the legitimate tag, the adversary waits until the reader initiates a new protocol session, where:

1. The reader generates a random number N_R \leftarrow PRNG(K_{old}) and sends it to the tag.
2. After receiving N_R \leftarrow PRNG(K_{old}), the adversary replies with M_1 \leftarrow PRNG(EPC_i \oplus N_R \oplus N_T) \oplus K_{old}, C_i \leftarrow C_{old}, D \leftarrow D \oplus N_R \oplus N_R \leftarrow N_T \oplus K_{old} \oplus N_R \oplus N_R \leftarrow N_T \oplus PRNG(C_i \oplus K_{old}) \oplus N_R \oplus N_R.

3. Once the reader receives the message, it computes V = H(RID \oplus N_R) and forwards M_1, D', C_i', E, N_R and V to the back-end database.

4. Once the back-end database receives the message, it proceeds as follows:
   - If each stored RID in the database, computes V = H(RID \oplus N_R) and compares it with the received V. Since the adversary has not manipulated the exchanged message from the reader to the back-end database, the back-end database authenticates the reader.
   - Assume that C_i \leftarrow C_i as an index to find the corresponding record in the database. The record would be found in its records for the field C_i \leftarrow C_i. Therefore the back-end database marks X as old.
   - Verifies whether PRNG(EPC_i \oplus N_R \oplus D \oplus K_{old}) \oplus K_{old} = M_1,
   - PRNG(EPC_i \oplus N_R \oplus D \oplus K_{old}) \oplus K_{old} = PRNG(EPC_i \oplus N_R \oplus D \oplus N_R \oplus N_R \oplus K_{old}) \oplus K_{old} = PRNG(EPC_i \oplus N_R \oplus D \oplus K_{old}) \oplus K_{old} = M_1 \leftarrow M_1.

   - Verifies whether N_T \oplus PRNG(C_i \leftarrow C_i \leftarrow K_{old}) = E' where:
     - N_T = D \oplus K_{old} = N_T \oplus N_R \oplus N_R \leftarrow N_T \oplus PRNG(K_{old} \oplus K_{old}) = N_T \oplus N_R \oplus N_R \leftarrow PRNG(K_{old} \oplus K_{old}) = E'.

   - Authenticates the adversary as a legitimate tag and computes M_2 and Info as follows, and forwards them to the reader:
     - M_2 \leftarrow PRNG(EPC_i \oplus N_R') \oplus P_{old}' and Info \leftarrow DATA \oplus RID.

5. Since X=old, updates the back-end database as follows:
   - C_{new} \leftarrow PRNG(N_T \oplus N_R').

   - Once the reader receives the message, it extracts DATA and forwards M_2 to the expected tag, which is the adversary.
only two protocol runs with negligible time and memory requirements [7].

### 3.3. Data Desynchronization Attack

In 2013 Deng and Zhu [11] have shown that the Habibi et al.’s protocol, can’t resist the data desynchronization attack either. Before the implementation of the data desynchronization attack, Adversary \( A \) needs to carry out a secret information disclosure attack that has been described in section 3.2. Thus \( A \) can disclose all the Secret Information of T, including EPCs, \( K_i \) and \( P_i \). Then \( A \) can easily launch the data desynchronization attack. The process of the data desynchronization attack is shown as follows. Firstly, \( A \) launches the secret information disclosure attack and retrieves any secret information in T, including EPCs, \( K_i \) and \( P_i \). Secondly, \( A \) eavesdrops the random number \( N_k \) generated by R and values \( C_i, M_1, D, E \) generated by T in the following protocol run, and it intercepts the message \( C_i, M_1, D, E \) from the tag to the reader. Thirdly, \( A \) computes \( N_k = D \oplus K_i, M_2 = PRNG(EPC_i \oplus N_k) \oplus P_i \) and forwards \( M_2 \) to T. Once T receives \( M_2 \), it authenticates Server S and updates the contents kept inside as \( K_i \rightarrow PRNG(K_i) \), \( P_i \rightarrow PRNG(P_i), C_i \rightarrow PRNG(N_k). \) Therefore, the tag has refreshed the secrets \( K_i, P_i, C_i \), while the back-end server will not do it. Thus, the shared secret between the tag and the back-end server may not be the same, which can bring system to a mess. After a successful data desynchronization attack, because \( A \) makes S and the valid tag T share the different secrets, S will not be authorized by T and T will not be authorized by S yet [11].

### 3.4. Traceability Attack

Castro et al. [7] have shown that the Habibi et al.’s protocol, like the original protocol, puts at risk the location privacy of tags’ holders because it is possible to track tags with a probability of 1 – between two successful runs of the authentication protocol. The following properties of the protocol are enough to trace a given tag \( T_k \) as long as it has not updated its internal values:

1. When the reader or possibly the adversary \( A \), which supplants a legal reader in a mutual authentication session, sends a random number \( N_k \) to the tag, it will answer with \( M_1, C_i \), where \( C_i \) is the tag’s index in the back-end database and will remain fixed as long as the tag does not participate in another successful protocol run to update its internal values.
2. Given that the tag’s reply to the reader’s (or adversary) query includes D and E,

Where \( D = N_{i} \oplus K_{i} \) and \( E = N_{i} \oplus PRNG(C_{i} \oplus K_{i}). \) It can be seen that if \( A \) computes \( Y \) as follows:

\[ Y \leftarrow D \oplus E = N_{i} \oplus K_{i} \oplus N_{i} \oplus PRNG(C_{i} \oplus K_{i}) = K_{i} \oplus PRNG(C_{i} \oplus K_{i}) \text{ then } Y \text{ only depends on } K_{i} \text{ and } C_{i} \text{ and these ones will remain fixed as long as the tag does not execute a new updating phase. Hence, } Y \text{ can be used as a value to perfectly trace } T \text{ [7].}]

### 4. Enhanced protocol

In order to eliminate the mentioned vulnerabilities in 3.1, 3.2 and 3.3 sections, we can modify the message E as:

\[ E = N_{i} \oplus PRNG(C_{i} \oplus K_{i}) \oplus P_{i} \]

Although the cited vulnerabilities are fixed by the above modification, but the traceability problem that has been discussed in section 3.4, still will be unsolved. Hence, we need to reconstruct the message E as following:

\[ E = PRNG(N_{i}) \oplus PRNG(C_{i} \oplus K_{i}) \oplus P_{i} \]

to provide a secure protocol against all cited attacks.

Fig.1, illustrates the \((i+1)\)th authentication phase of proposed protocol. The detailed steps of the authentication phase are presented as follows.

1) The reader R generates a random number \( N_k \) and sends it to the tag T.
2) T receives \( N_k \), generates a random number \( N_R \), computes \( M_1, D, E \) and finally sends \( M_1, D, E \) to R, where \( M_1 = PRNG(EPC_{i} \oplus N_k \oplus N_{i} \oplus K_{i}) \) and \( D = N_{i} \oplus K_{i} \) and \( E = PRNG(N_{i}) \oplus PRNG(C_{i} \oplus K_{i}) \oplus P_{i}. \)
3) When R receives the message, it computes \( V = h(RID \oplus N_{k}) \) and forwards \( M_1, D, C_{i}, E, N_{k}, V \) to the back-end server S.
4) After S receiving \( M_1, D, C_{i}, E, N_{k}, V \), it proceeds as follows.

- For each RID stored in the database, it computes \( h(RID \oplus N_{k}) \) and compares it with the received \( V \) to verify R legitimacy.
- If \( C_{i} = 0 \), which means that it is the first access to the tag, it proceeds as follows, iteratively:
  a) Picks up an entry \((K_{\text{old}}, P_{\text{old}}, C_{\text{old}}, K_{\text{new}}, P_{\text{new}}, C_{\text{new}}, \text{RID}, \text{EPCs}, \text{DATA})\) stored in database.
  b) Verifies whether \( M_1 \oplus K_{\text{old}} = PRNG(EPC_{i} \oplus N_{k} \oplus D \oplus K_{\text{old}}) \) or \( M_1 \oplus K_{\text{new}} = PRNG(EPC_{i} \oplus N_{k} \oplus D \oplus K_{\text{new}}) \), and marks X as old or new provided that the verification process is satisfied based on the new record or the old record.
- Otherwise, S uses \( C_{i} \) as an index to find the corresponding record in the database and verify whether \( PRNG(EPC_{i} \oplus N_{k} \oplus D \oplus K_{X}) \oplus K_{X} \oplus K_{i} \) = \( M_1 \). If “No” the protocol aborts.
- Verify whether \( PRNG(N_{i}) \oplus PRNG(C_{i} \oplus K_{i}) \oplus P_{i} = E \). If “No” the protocol aborts.
- Computes \( M_2 \) and Info and forwards them to R, where \( M_2 = PRNG(EPC_{i} \oplus N_{i}) \oplus P_{X} \)
and Info = DATA ⊕ RID,

- If X = new, updates the database as follows:
  \[ K_{\text{old}} = K_{\text{new}}, \quad K_{\text{new}} \leftarrow \text{PRNG}(K_{\text{new}}), \]
  \[ P_{\text{old}} = P_{\text{new}}, \quad P_{\text{new}} \leftarrow \text{PRNG}(P_{\text{new}}), \]
  \[ C_{\text{old}} = C_{\text{new}}, \quad C_{\text{new}} \leftarrow \text{PRNG}(N_T \oplus N_R). \]
- Else
  \[ C_{\text{new}} \leftarrow \text{PRNG}(N_T \oplus N_R). \]

5) Once R receives the message, it extracts DATA as Info ⊕ RID and forwards M2 to T.

6) When T receives the message, it verifies whether PRNG(EPCs ⊕ N_T) = M2 ⊕ P_i.
   If “No” the protocol aborts. Else T authenticates S and updates the contents kept inside as
   \[ K_{i+1} \leftarrow \text{PRNG}(K_i), \]
   \[ P_{i+1} \leftarrow \text{PRNG}(P_i), \quad C_{i+1} \leftarrow \text{PRNG}(N_T \oplus N_R). \]

\[ \text{Fig. 1 (i + 1)th authentication phase of proposed protocol} \]

4.1. Security analysis of enhanced protocol

In this section security and privacy of proposed protocol is evaluated against various threats.

4.1.1. Secret Information Disclosure Attack

The proposed protocol resists to this attack, because of XOR P_i with E. By this modification, step 2 of this attack has not established, because the adversary does not know
the value of \( P_i \) and cannot obtain \( N_T \) and \( K_X \) values as follow:

\[
\forall \ i=0...N_d \ does \ as \ follows:
\begin{align*}
K &\leftarrow i, \\
N_T &\leftarrow D \oplus K_0,
E &\neq N_T \oplus PRNG(C_i \oplus K_i) \oplus P_i.
\end{align*}
\]

### 4.1.3. Replay Attack

Updating the secret values in each authentication process and the prevention of Secret Information disclosure, and in particular using random values \( N_0 \) and \( N_T \) for making the transition massages, an adversary cannot send obtained information in the next round of the authentication instead of legal tag, because of variation of massages.

### 4.1.4. Traceability Attack

In the proposed protocol to resist this attack that has been discussed in section3.4, \( N_T \) has been replaced by \( PRNG(N_d) \) in the message E, so in the proposed attack the result of XOR messages D and E is not fixed because of the random value \( N_T \) has not been deleted.

\[
\begin{align*}
D &= N_T \oplus K_i \\
E &= PRNG(N_T) \oplus PRNG(C_i \oplus K_i) \oplus P_i, \\
Y &= D \oplus E = N_T \oplus K_i \oplus PRNG(N_T) \oplus PRNG(C_i \oplus K_i) \oplus P_i,
\end{align*}
\]

As a result the value of \( Y \) is not fixed in each authentication phase although the updating phase has not been executed.

### 4.1.5. Privacy

In proposed protocol the privacy problem has been solved because of avoidance of Secret Information disclosure and traceability attacks.

### 4.1.6. DoS Attack

If an adversary prevents the tag from updating it’s secret information by intercepting M2, the server is asynchronous with the tag and at a result the communication between them will be intercepted, but In this case by keeping \( C_{old} \) value in the database, in the next authentication session the server supposed that tag authentication process in the previous session is not completed successfully. Then it authenticates the tag by it’s \( C_{old} \) and only updates it’s \( C_{new} \).

### 4.1.7. Tag Impersonation Attack

#### 4.1.7.1. Desynchronization Attack

An adversary requires tag’s Secret Information for desynchronization attack that has been avoided in proposed protocol. Also keeping \( K_{old}, C_{old}, P_{old} \) values in back-end server can help to avoid desynchronization attack occurrence.

The proposed protocol resists to tag impersonation attack that has been discussed in section 3.2, by changing the structure of E as follow: \( E=PRNG(N_T) \oplus PRNG(C_i \oplus K_i) \oplus P_i. \)

By this modification the back-end server cannot confirm \( E’ \) as below:

\[
\begin{align*}
PRNG(N_T') \oplus PRNG(C_{old} \oplus K_{old}) \oplus P_i = E' \\
N_T' &= D' \oplus K_{old} = N_T \oplus N_0 \oplus N_r \Rightarrow PRNG(N_T') \oplus PRNG(C_{old} \oplus K_{old}) \oplus P_i = PRNG(N_T \oplus N_0 \oplus N_r) \oplus PRNG(C_{old} \oplus K_{old}) \oplus P_i \neq E'.
\end{align*}
\]

#### 4.1.7.2. Database Loading

In this protocol, similar to previous version, \( C_i \) is used as an index to access the database which requires record-by-record operations and verifications only in the first access and the index for the tag can be set accordingly. As for any later on accesses, only \( C_i \) will be needed as an index. Thus, the performance of the system has not been changed.

<table>
<thead>
<tr>
<th>Table1. Comparison of authentication protocols</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Authentication</strong></td>
</tr>
<tr>
<td>Desynchronization Attack</td>
</tr>
<tr>
<td>Replay Attack</td>
</tr>
<tr>
<td>Tracking Attack</td>
</tr>
<tr>
<td>Privacy</td>
</tr>
<tr>
<td>DoS Attack</td>
</tr>
<tr>
<td>Tag Impersonation Attack</td>
</tr>
<tr>
<td>Database Loading</td>
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</table>

### 5. Conclusions

In this paper, we demonstrated some security problems of Habibi et al.’s RFID authentication protocol. We discussed a powerful and practical attack on this protocol which is secret information disclosure. This attack leads to desynchronization attack. Moreover, we explained the tag impersonation and traceability attacks on this protocol. To eliminate all cited vulnerabilities, we enhanced this protocol by reconstructing the message E in a new way. Finally the enhanced protocol, has been compared with the existing EPC-C1-GEN2-based RFID authentication protocols in terms of security and privacy.
The comparison results showed that the enhanced protocol can enhance the security and privacy in RFID systems.

Reference