A Note on the Security of Two Improved RFID Protocols

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ABSTRACT

Recently, Baghery et al. [1, 2] presented some attacks on two RFID protocols, namely Yoon and Jung et al. protocols, and proposed the improved version of them. However, in this note, we show that the improved version of the Jung et al. protocol suffers from desynchronization attack and the improved version of the Yoon’s protocol suffers from secret disclosure attack. The success probability of the desynchronization attack against the improved version of the Jung et al. protocol is \( (1 - 2^{-2n})^2 \), where \( n \) is length of the protocol parameters. The attack can be accomplished with just three runs of the protocol. The success probability of the secret disclosure attack against the improved version of the Yoon’s protocol is almost 1, while the complexity is just two runs of the protocol and doing \( 2^{16} \) off-line evaluations of PRNG function.

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1 Introduction

Baghery et al. [1, 2] recently proposed an attempt on enhancing the privacy of two recent authentication schemes for low-cost RFID systems, i.e., Yoon [3] and Jung et al. [4] protocols. The first protocol was an enhancement of Yoon’s protocol [3], which is an improvement over Yeh et al.’s protocol [5] and has already received several security analyses, e.g., see [6, 7].

In this letter, the security of the improved version of the protocols are scrutinized and important security pitfalls are shown.

The rest of the letter is organized as follows: In Section 2, we review the improved Yoon’s protocol and present the secret disclosure attack against it. The description of the Jung et al. protocol and the desynchronization attack against it are explained in Section 3. Section 4 gives some solutions to address the weaknesses of the protocols against the attacks presented in this letter. Finally the paper concludes in Section 5.

2 On the security of the improved Yoon’s protocol

2.1 Protocol Description

As depicted in Figure 1, in this section, using the notation depicted in Table 1, we give a brief description of the improved Yoon’s protocol. This protocol has two phases: the initialization phase and the \((i + 1)^{th}\) authentication phase which is described as follows:

**Initialization Phase:** In this phase, the manufacturer generates random values for \( K_0, P_0 \) and \( C_0 \), respectively and sets the values of the record in
the tag, i.e., \( K_0, P_0, C_0 \), and the corresponding record in the back-end database \( K_{old} = K_{new} = K_0, P_{old} = P_{new} = P_0, C_{old} = C_{new} = 0 \).

**Authentication Phase:** The authentication phase of the improved Yoon’s protocol at its \((i+1)^{th}\) run is as follows:

1. The reader generates a random number \( N_R \) and sends it to the tag.
2. The tag receives \( N_R \), generates random numbers \( N_T \) and \( N_3 \), computes \( M_1, D, C_1, E \) as below and sends tuple \((M_1, D, C_1, E)\) to the reader:
   \[
   M_1 \leftarrow PRNG(EPC_s \oplus N_R \oplus N_T) \oplus K_i
   \]
   \[
   D \leftarrow N_T \oplus K_i
   \]
   \[
   C_1 \leftarrow C_i \oplus N_3
   \]
   \[
   E \leftarrow PRNG(N_T) \oplus PRNG(C_i \oplus K_i)
   \]
3. Once the reader receives the message, it computes \( V = H(RID \oplus N_R) \) and forwards tuple \((M_1, D, C_1, E, N_R, V)\) to the back-end database DB.
4. DB receives the tuple \((M_1, D, C_1, E, N_R, V)\) and proceeds as follows:
   - It verifies whether \( H(RID \oplus N_R) \oplus V \) to authenticate the reader.
   - If the reader has been authenticated, for any entry in database it computes \( I_X = M_1 \oplus K_X \), for \( X \in \{old, new\} \), and checks whether \( I_X = PRNG(EPC_s \oplus N_R \oplus D \oplus K_X) \), to determine whether \( X = old \) or \( new \). If it finds related record, it verifies whether \( E \oplus PRNG(D \oplus K_X) \oplus PRNG(C_i \oplus K_X) \) to authenticate the tag. If the tag has been authenticated, DB computes the following values and sends \((M_2, Info, MAC)\) to the reader:
     \[
     N_T \leftarrow D \oplus K_X
     \]
     \[
     M_2 \leftarrow PRNG(EPC_s \oplus N_T) \oplus P_X
     \]
     \[
     Info \leftarrow DATA \oplus RID
     \]
     \[
     MAC \leftarrow H(DATA \oplus N_R)
     \]
     \[
     N_3 \leftarrow C_i \oplus C_X
     \]
   - If \( X = new \), DB updates its values as follows:
     \[
     K_{old} \leftarrow K_{new} \leftarrow PRNG(K_{new} \oplus N_3),
     \]
     \[
     C_{old} \leftarrow C_{new} \leftarrow PRNG(N_T \oplus N_R \oplus P_{new}),
     \]
     \[
     P_{old} \leftarrow P_{new} \leftarrow PRNG(P_{new}).
     \]
   - Else, DB updates its values as follows:
     \[
     K_{new} \leftarrow PRNG(K_{new} \oplus N_3),
     \]
     \[
     C_{new} \leftarrow PRNG(N_T \oplus N_R \oplus P_{new}).
     \]
5. Once the reader receives the message, it verifies whether \( H(DATA \oplus N_R) \oplus MAC \). If “Yes” forwards \( M_2 \) to the tag; otherwise the protocol aborts.
6. Once the tag receives the message, it verifies
6. For each RID, computes:

- $V = H(RID \oplus N_r)$
- If $V = V'$, authenticates the tag.
- If $I_{tag} = M_k \oplus K_{new}$:
  - $X = \text{new}$
  - $E_{\text{tag}} = \text{PRNG}(EPC_s \oplus N_r \oplus D \oplus K_{new})$
- Else:
  - $I_{tag} = M_k \oplus K_{old}$
  - $X = \text{old}$
  - $E_{\text{tag}} = \text{PRNG}(EPC_s \oplus N_r \oplus D \oplus K_{old})$

- $V' = H(RID \oplus N_r)$

If $V' = V$, goes to updating phase.

- $C_{new} = \text{PRNG}(N_r \oplus N_k \oplus P_i)$
- $P_{new} = \text{PRNG}(P_i)$
- $K_{new} = \text{PRNG}(K_i \oplus N_3)$
- $P_{new} = \text{PRNG}(P_i)$
- $C_{new} = \text{PRNG}(N_r \oplus N_k \oplus P_i)$

- $P_{new} = \text{PRNG}(P_i)$
- $K_{new} = \text{PRNG}(K_i \oplus N_3)$
- $C_{new} = \text{PRNG}(N_r \oplus N_k \oplus P_i)$

### Remarks

**Remark 1.** In Step 4, the designers only update $C_{new}$. However, we consider it as a typo because $K_{new}$ should also be updated; otherwise it will be easy to desynchronize the tag and the reader by just blocking the last message sent from the reader to the tag. In that case, DB has updated the tag’s record based on $N_3$, while the tag has not. In the next session, assuming that the tag generates $N'_3$, DB runs Step 4 but does not update the value of $K_{new}$ while the tag uses $N'_3$ to update its key, which desynchronize the tag and DB with a high probability. Hence, we assumed that in Step 4 of the protocol, DB also updates $K_{new}$. However, this assumption does not simplify the presented analysis in the next section.

### 2.2 Secret Disclosure Attack on the Protocol

Designers of the improved protocol based their protocol on the Yoon’s protocol which uses a 16-bit PRNG. In addition, they have presented an attack with the complexity of $2^{16}$ offline computation against the Yoon’s protocol. In this section, we show that it is possible to extract all secret parameters of the improved version of the Yoon’s protocol with almost the same complexity. To disclose the secrets of the tag, the adversary does as follows:

#### Learning Phase

- **Step 1:** Given the target tag $T_j$, the adversary eavesdrops a session of the protocol between the tag and the reader and stores the following values, but it blocks the reader’s feedback to the tag (hence the tag will not update its parameter in this stage):
  - $M_1 = PRNG(EPC_s \oplus N_R \oplus N_T) \oplus K_i, D =$
\(N_T \oplus K_i, C_i = C_i \oplus N_3, E = PRNG(N_T) \oplus PRNG(C_i \oplus K_i)\) and \(M_2 = PRNG(EPC_s \oplus N_T) \oplus P_X\)

**Step 2:** The adversary impersonates the reader and sends \(N_T\) to the tag and stores its responses which are as follows: \(M'_i = PRNG(EPC_s \oplus N_R \oplus N'_T) \oplus K_i, D' = N'_T \oplus K_i, C_i = C_i \oplus N'_3\) and \(E' = PRNG(N'_T) \oplus PRNG(C_i \oplus K_i)\)

**Secret Disclosure Phase**

- **Step 1:** With the complexity of \(2^{16}\) the adversary finds a value for \(x'\) that satisfies \(PRNG(x) \oplus PRNG(x \oplus \Delta) = M_1 \oplus M'_1\), where \(\Delta = D \oplus D'\).
- **Step 2:** Given \(x'\) form **Step 1**, the adversary extracts \(K_i = M_1 \oplus PRNG(x)\).
- **Step 3:** Given \(K_i\) form **Step 2**, the adversary extracts \(N'_T = D \oplus K_i\) and \(EPC_s = X \oplus N_T \oplus N_R\).
- **Step 4:** Given \(N_T\) and \(EPC_s\) form **Step 3**, the adversary extracts \(P_i = M_2 \oplus PRNG(EPC_s \oplus N_T) = X' \oplus N_T \oplus N_R\).
- **Step 5:** The adversary can use \(E\) and \(E'\) to ensure the correctness of the extracted values.

Given the above attack, the adversary knows all sufficient information to impersonate the tag to the reader or the reader to the tag, hence it can be also considered as a tag/reader impersonation attack. In addition, impersonating the reader, the adversary will desynchronize both tag and the reader and it is enough to trace the target tag at any time, given that it will not update its secret parameters through DB any more. Finally, given the value of \(P_i\) from **Step 4** and its updating rule which is \(P_{i+1} = PRNG(P_i)\), even without desynchronizing the tag and the reader any adversary who has an estimation of the number of the successful communications of the tag and the reader can trace the tag which compromises the tag holder’s privacy.

**3 On the Security of the Improved Jung et al. Protocol**

**3.1 Protocols Description**

As depicted in Figure 2, in this section, using the notation depicted in Table 1, we describe the improved version of the Jung et al. protocol [1, 2]. More precisely, the protocol can be described as follows:

**Protocol 2:** This protocol is composed of five steps:

- **Step 1:** The RFID reader (\(R_i\)) sends \(\text{Hello}(ID_r)\) to the RFID tag \(T_j\).
- **Step 2:** The RFID tag \(T_j\) generates a random number \(N_T\) and calculates \(\alpha = H(ID_t \oplus N_T), \beta = K_i \oplus N_T \oplus C_i\) and \(\gamma = HMAC_{ID_t}(T_i, ID_r, N_T)\) and transmits tuple \((\alpha, \beta, \gamma, ||T_i||ID_r)\) to the reader \(R_i\).
- **Step 3:** The RFID reader (\(R_i\)) transmits the received tuple to the database (DB).
- **Step 4:** DB receives the tuple sent by \(R_i\), extracts \(I_X = K_X \oplus C_X \oplus \beta\) for each tuple \((ID_t, K_X, C_X)\), where \(X \in \{\text{old}, \text{new}\}\), and verifies whether \(H(ID_t \oplus I_X) = \alpha\). Then it checks whether \(\gamma = HMAC_{ID_t}(T_i, ID_r, I_X)\) to authenticate the tag. If the tag has been authenticated, DB calculates \(\Psi = HMAC_{ID_t}(T_i + 1, ID_r, I_X)\) and sends it through the reader to \(T_j\). DB also updates the tag’s records as \(K_{old} \leftarrow K_{new} \leftarrow H(K_X \oplus N_T)\) and \(C_{old} \leftarrow C_{new} \leftarrow H(N_T \oplus ID_r)\).
- **Step 5:** To authenticate DB, the tag verifies the received value from DB by checking whether \(\Psi = HMAC_{ID_t}(T_i + 1, ID_r, I_X)\). If DB has been authenticated successfully, the tag updates its parameters as \(K_{i+1} \leftarrow H(K_i \oplus N_T)\) and \(C_{i+1} \leftarrow H(N_T \oplus ID_r)\).

**3.2 Desynchronization Attack on the Protocol**

Designers of the improved protocol claimed that [2, p.146] since DB keeps a record of both new and old secret keys of the tag it is not possible to desynchronize \(T\) and DB. However, in this section we present an efficient attack to desynchronize the tag which contradicts the designers’ claim. To desynchronize the tag, the adversary does as follows:

**Learning Phase**

- **Step 1:** Assuming that the target tag participated in an authentication process, when \(T_j\) transmits tuple \((\alpha, \beta, \gamma, ||T_i||ID_r)\) to the reader \(R_i\), the adversary intercepts it but keeps a record of it.
- **Step 2:** In the next attempt of the reader to authenticate \(T_j\), the tag generates a new random value \(N'_T\) and calculates \(\alpha' = H(ID_t \oplus N'_T), \beta' = K_i \oplus N'_T \oplus C_i\) and \(\gamma' = HMAC_{ID_t}(T_i, ID_r, I_X)\) and transmits tuple \((\alpha', \beta', \gamma', ||T_i||ID_r)\) to the reader \(R_i\).
- **Step 3:** \(R_i\) receives the received tuple from DB.
- **Step 4:** DB receives the tuple sent by \(R_i\), authenticates the tag, calculates \(\Psi = HMAC_{ID_t}(T_i + 1, ID_r, I_X)\) and sends it through the reader to \(T_j\). DB also updates the tag’s records as \(K_{old} \leftarrow K_{new} \leftarrow H(K_X \oplus N'_T)\) and \(C_{old} \leftarrow C_{new} \leftarrow H(N'_T \oplus ID_r)\).
- **Step 5:** The tag also authenticates DB successfully and updates its parameters as \(K_{i+1} \leftarrow H(K_i \oplus N'_T)\) and \(C_{i+1} \leftarrow H(N'_T \oplus ID_r)\).

**Desynchronization Phase**

- **Step 1:** When the reader tries to communicate with a tag \(T_i\), the adversary impersonates that tag and sends the stored tuple from **Step 1** of the learning phase of this attack to the reader, i.e., \((\alpha, \beta, \gamma, ||T_i||ID_r)\), where \(\alpha = H(ID_t \oplus N_T), \beta = K_i \oplus N_T \oplus C_i\) and \(\gamma = HMAC_{ID_t}(T_i, ID_r, N_T)\).
- **Step 3:** \(R_i\) transmits the received tuple to the DB.
Figure 2. The improved Jung et al. protocol [4]

- **Step 4**: DB receives the tuple sent by \( R_i \), based on the old secret parameters of \( T_j \), authenticates \( T_j \) as the tag, calculates \( \Psi' = HMAC_{ID_i}(T_t + 1, ID_r, N_T) \) and sends it through the reader to the tag. DB also updates the \( T_j \)'s records as \( K_{old} \leftarrow K_{new} \leftarrow H(K_X \oplus N_T) \) and \( C_{old} \leftarrow C_{new} \leftarrow H(N_T \oplus ID_i) \).

At the end of the given procedure, the tag’s records of secret parameters are \( K_{i+1} = H(K_i \oplus N_T^2) \) and \( C_{i+1} = H(N_T^2 \oplus ID_i) \) which does not match any record of the server with the probability of \( (1 - 2^{-2n})^2 \), where \( n \) is the length of each parameter. Hence, the tag and the database have been desynchronized and they will not authenticate each other henceforth. The success probability of the given attack is \( (1 - 2^{-2n})^2 \) while the complexity is just three runs of the protocol.

**Remark 2.** Although, in the protocol a time stamp \( T_t \) is used, however, it does not verify by any party of the protocol. Hence, it cannot prevent the given attack.

**4 Recommendations**

Our attacks in this letter on the improved version of the Yoon’s protocol employs the fact that a 16-bit PRNG can be easily inverted and it may not be feasible to design a secure protocol just using several calls to 16-bit PRNGs. This fact has already been used for security analysis of some other EPC C-1 G-2 compliant protocols, e.g., see [8–10]. Hence, we suggest to use lightweight block ciphers, e.g., SIMON [11], or lightweight PRNGs with longer output, e.g., [12], to improve the security of EPC C-1 G-2 compliant protocols.

The second attack that we have presented in this letter was on the improved version of the Jung et al. protocol [4]. The main observation was the fact that a party of protocol, i.e., the reader, does not contribute to the randomness of the messages. This weakness has already been used for example to cryptanalysis of RAPP-protocol [13] also, see [14, 15]. Hence, it should be vital for any protocol to be randomized by all protocol parties.

**5 Conclusions**

In this letter, we analyzed the security of two recent protocols published in [1, 2] and showed their important security pitfalls. The vulnerabilities of the analyzed protocols against such simple attacks show that the analyzed protocols were incorrectly designed. Hope our result helps the direction of designing secure protocols for constrain RFID tags and avoiding such flaws in future protocols.
Acknowledgment
This work was supported by Shahid Rajaee Teacher Training University under contract number 7502.

References


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