Communication-efficient Certificate Revocation Management for Advanced Metering Infrastructure*

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Abstract—Advanced Metering Infrastructure (AMI) forms a communication network for the collection of power data from smart meters in Smart Grid. As the communication within an AMI needs to be secure, public-key cryptography (PKC) can be used to reduce the overhead of key management. However, PKC still has certain challenges in terms of certificate revocation and management. In particular, distribution and storage of the Certificate Revocation List (CRL), which holds the revoked certificates, is a major challenge due to its overhead. To address this challenge, in this paper, we propose a novel revocation management approach by utilizing cryptographic accumulators which reduces the space requirements for revocation information significantly and thus enables efficient distribution of such information to all smart meters. We implemented the proposed approach on both ns-3 network simulator and an actual AMI testbed developed at FIU and demonstrated its superior performance with respect to traditional methods for CRL management.

Index Terms—Advanced Metering Infrastructure, One-way cryptographic accumulator, Certificate revocation lists, Public Key Infrastructure

I. INTRODUCTION

The existing power grid is currently going through a major transformation to enhance its reliability, resiliency, and efficiency by enabling networks of intelligent electronic devices, distributed generators, and dispersed loads [1], which is referred to as Smart(er) Grid. Advanced Metering Infrastructure (AMI) network is one of the renewed components of Smart Grid that helps to collect smart meter data using a two-way communication [2]. Smart meters are typically connected via a wireless mesh network with a gateway (or access point) serving as a relay between the meters and the utility company.

The security requirements for the AMI network are not different from the conventional networks as confidentiality, authentication, message integrity, access control, and non-repudiation are all needed to secure the AMI. Confidentiality is required to prevent exposure of customer’s private data to unauthorized parties while integrity is necessary to ensure that power readings are not changed for billing fraud. Furthermore, authentication is crucial to prevent any compromised smart meters communicating with other smart meters. As in the case of conventional networks, these requirements can be met by using either symmetric or asymmetric key cryptography. However, in both cases, management of the keys is a major issue in terms of automation, efficiency, and cost. Due to the huge overhead of maintaining symmetric keys [3], using public-keys can provide some advantages and makes it easier to communicate with IP-based outside networks when needed [4]. Moreover, according to National Institute of Standards and Technology (NIST), Public Key Infrastructure (PKI) is more appropriate for large AMI depending on the number of possible communicating pairs of devices [5]. As an example, companies such as Landis&Gyr and Silver Spring Networks use PKI to provide security for millions of smart meters in the US [6]. In such a PKI, the public-keys for smart meters and utilities are stored in certificates which are issued by Certificate Authorities (CAs). The employment of certificates in AMI requires management of them which include the creation, renewal, distribution and revocation. In particular, the certificate revocation and its association with smart meters are critical and have the potential to impact the performance of AMI applications significantly [7]. Therefore, we focus on efficient handling of this issue in this paper.

To recap, there are several reasons that necessitate revoking certificates, such as key compromise, certificate compromise, excluding malicious meters, renewing devices, etc. As a result, when processing certificates, one has to check a certificate’s revocation status before accepting it. The Certificate Revocation List (CRL) is a commonly used method for certificate revocation scheme that keeps the list of revoked certificates serial numbers and revocation dates. The status of a certificate can be determined by checking whether it is in the CRL or not. Considering the large number of smart meters in an AMI and the fact that the expiration period of a certificate is relatively longer (and even lifelong in particular applications [6]) than that of other conventional systems such as websites [8], the CRL size will grow significantly as time passes. Besides, there are several known incidents that suddenly cause revocation of so many certificates. For instance, a recent discovery of a chip deficiency on RSA key generation caused revocation of more than 700K certificates of devices which deployed this specific chip [9] and renowned Heartbleed vulnerability caused the revocation of millions of certificates, immediately [10].

The above cases indicate that independent of the aforementioned revocation reasons, if there is a new vulnerability in the used algorithms for certificates, a massive number of revocations may additionally occur. Thus, dealing with the overhead of CRLs become a burden both for the resource-constrained smart meters in terms of storage and for the AMI infrastructure which is typically restricted in terms of bandwidth to distribute these CRLs. The latter is particularly critical since reliability and efficiency of AMI data communication is crucial in the functioning of the distribution systems in power grid.

In this paper, we propose a communication-efficient revocation or CRL management scheme for AMI networks by using RSA accumulators [11]. RSA accumulator is a cryptographic tool which is able to represent a set of values with a single accumulator value (i.e., digest a set into a single value). Moreover, it provides a mechanism to check whether an element is in the set or not which implicitly means that cryptographic accumulators can be used for efficient membership testing. Due to the attractiveness of size, in this paper, we adapt RSA accumulators for our needs by introducing several novel elements. Specifically, an accumulator manager within the utility company (UC) is tasked with collection of CRLs from CAs and accumulating these CRLs (i.e., revoked certificates’
serial numbers) to a single accumulator value which will then be distributed to the smart meters. Along with the accumulator value, we also introduce and distribute a customized non-revoked proof for allowing a smart meter to check whether another meter’s certificate is revoked without a need to refer to the CRL file.

The computation and communication related aspects of the proposed approach are assessed via simulations in ns3 network. In addition, we built an actual testbed at FIU using in-house smart meters to assess the performance realistically. We compared our approach with the other methods that use conventional CRL schemes and Bloom-filters. The results show that the proposed approach significantly outperforms the other existing methods in terms of reducing the communication overhead that is measured with the completion time. The overhead in terms of computation is not major and can be handled in advance within the utility that will not impact the smart meters. This paper is organized as follows: In the next two sections, we summarize the related work and the background. Section IV introduces the threat model. Section V present the proposed approach with its features. Section V and VI is dedicated to security analysis and experimental validation. The paper is concluded in Section VII.

II. RELATED WORK

A. CRL Management in AMIs

The studies [7], [13] investigated different revocation management aspects such as aspects such as short-lived-certificate scheme, tamper-proof device scheme, Online Certificate Status Protocol (OCSP), conventional CRL, and compressed CRL for AMI. However, these studies just state the importance of revocation management for AMI and provide a general overview. To summarize the basics, in the OCSP approach [14], an online and interactive OCSP server stores revocation information and responds to the queries to check the status of a certificate. An improved version of this approach is called OCSP “stapling” [15] where the smart meters query the OCSP server at certain intervals and obtains a timestamped OCSP response which is directly signed by the CA. This response is included (i.e., stapled) in the certificate as a proof that it is not revoked. Even though the OCSP approaches can be advantageous by not requiring distribution and storage of revocation information on smart meters, deploying them in an AMI environment is not attractive since this will require frequent access to a remote server which will create enormous traffic from all smart meters that may disrupt other AMI services. Furthermore, it violates a common habit where AMIs are maintained as isolated networks by allowing access from smart meters to CAs.

The first comprehensive study that focused on reducing the revocation management overhead for AMI was based on Bloom Filters [16]. The size of CRLs was reduced by Bloom Filters. However, Bloom Filters suffer from false positives and may eventually require accessing the CA to check the validity of a certificate. Our proposed scheme, on the other hand, never requires accessing a remote server and provide a better reduction on CRL size. The study in [17] used distributed hash tables (DHT) to reduce the CRL size. Although this study provides a reduction in CRL size, it suffers from additional inter-meter communication overhead for accessing the CRL information.

We would like to note that a very preliminary version of this work was published in [18]. This work, however, contains at least 60% additional material and most of the previous material has been changed significantly. First, we improved the proposed approach by utilizing Eulers Theorem for an improved computational performance. Second, we extended our threat model to new attack types that were not considered in the conference version. In this regard, we changed our approach in several ways: We proposed to use an initial secret during accumulation. We then introduced a non-revoked proof concept that was not used before in any of the revocation works. This required major changes to the accumulation process which was not in [18]. We finally proposed an extensive certificate verification protocol as countermeasures to the new threats. This also required proposing a new secure multi-level AMI architecture as opposed to the monolithic architecture used in [18]. The experiments are also completely changed: We built an AMI testbed utilizing IEEE 802.11s-based mesh network protocol to conduct more realistic tests. The conference version had only simulation results. In addition, we added several new experiments with accumulator computation overhead under various assumptions.

B. Cryptographic Accumulators

Cryptographic accumulators were first introduced by Benaloh and DeMare [19]. After their first appearance, there have been studies [11], [20], [21] offering to use them for membership testing. However, these studies solely focused on building the cryptographic fundamentals of accumulators, and thus, omit application specific issues and security features when deploying them. In addition, these studies are offering to use accumulators for membership testing by accumulating a valid list. Considering AMI, accumulation of valid smart meter’s certificates to provide a revocation mechanism would constitute a significant overhead due to the fact that revocation frequency is less than that of creating new certificates (i.e., no need to update the accumulator each time when a new smart meter is added to AMI) and number of revoked certificates is also less than the number of valid certificates which affects the required computation time significantly [10]. Our approach mitigates these drawbacks by addressing security and application specific issues and offering to use CRLs instead of valid certificates.

III. PRELIMINARIES

A. Background on Cryptographic Accumulators

Benaloh and De Mare [19] introduced the cryptographic accumulator concept which is a one-way hash function with a special property of being quasi-commutative. A quasi-commutative function is a special function $F$ such that $y_0, y_1, y_2 \in \mathbb{Y}$:

$$F(F(y_0, y_1), y_2) = F(F(y_0, y_2), y_1)$$

(1)

The properties of this function can be summarized as follows: 1) it is a one-way function, i.e., hard to invert; 2) it is a hash function for obtaining a secure digest $A$ (i.e., accumulator value) where $A = F(F(y_0, y_1), y_2, ..., y_m)$ for a set of values $\{y_0, y_1, y_2, ..., y_m\} \in \mathbb{Y}$; 3) it is a quasi-commutative hash function which is different from other well-known hash functions such that the accumulator value $A$ does not depend on the order of $y_i$ accumulations.

These properties allow cryptographic accumulators to be used for a condensed representation of a set of elements. In addition, since the resulting accumulated hashes of $y_i$ ($\mathbb{Y} = \{y_i; \ 0 < i < m\}$) stays the same even if the order of hashing is changed, it can be used for efficient membership testing by using a special value called witness value $w_i$. For instance, the witness $w_j$ of corresponding $y_j$ is calculated by accumulating all $y_i$ except the case where $i \neq j$ (e.g., $w_j = F(F(y_0, y_1), ..., y_{j-1}, y_{j+1}, ..., y_m)$). Then, when necessary
any of the members can check whether \( y_j \) is also a member of the group by just verifying whether \( \mathcal{F}(w_j, y_j) = \mathcal{A} \). Note that, because \( \mathcal{F} \) is a one-way function, it would be computationally infeasible to obtain \( w_j \) from \( y_j \) and \( \mathcal{A} \). However, there is a risk for collusion in this scheme when an adversary can come up with \( w_j' \) and \( y_j' \) pairs where \( y_j' \notin \mathcal{Y} \) to obtain the same accumulator value: \( \mathcal{F}(w_j', y_j') = \mathcal{A} \). In the literature, there is already a cryptographic accumulator, namely the RSA construction \([22]\) which guarantees that finding such pairs is computationally hard by restricting the inputs to the accumulator function to be prime numbers only. This scheme is known as collision-free accumulator that enables secure membership testing (i.e., without any collision). Therefore, in this paper, we chose to employ RSA construction which is elaborated next.

B. RSA Accumulator

RSA accumulator \([22]\) has a RSA modulus \( N = pq \), where \( p \) and \( q \) are strong primes. The RSA accumulation value \( \mathcal{A} \) is calculated on consecutive modular exponentiation of prime numbers set \( \mathcal{Y} = \{y_1, \ldots, y_n\} \) and \( g \) is quadratic residue of \( N \) as follows:

\[
\mathcal{A} = g^{y_1 \cdots y_n} \pmod{N}
\]  

(2)

The witness \( w_j \) of corresponding \( y_j \) is calculated by accumulating all values except \( y_j \):

\[
w_j = g^{y_1 \cdots y_{j-1} y_{j+1} \cdots y_n} \pmod{N}
\]  

(3)

Then, the membership testing can be done via a simple exponential operation by comparing the result with the accumulator value \( \mathcal{A} \):

\[
w_j \leftrightarrow \mathcal{A}
\]  

(4)

The described accumulator scheme so far basically allows generation of a "witnesses" to prove that an item is in the set. A more advanced accumulator would offer proofs of non-membership which proves that an item is NOT in the set \([23]\). For this scheme, let us assume any \( x \notin \mathcal{Y} = \{y_1, \ldots, y_n\} \). In a nutshell, the non-witness values can be computed by the following steps: Let \( u \) denote \( \prod_{i=1}^{n} y_i \), the scheme finds non-witness \( nw_{1:b} \) value pairs of \( x \) by solving the equation of \( nw_{1:b} x + b \times x = 1 \) using the Extended Euclidean algorithm.

Then, the scheme computes a value \( nw_{2:b} \) such that:

\[
\text{nw}_{2:b} = g^{-b} \pmod{N}
\]  

(5)

After these steps, the non-membership testing can be done via a simple exponential operation by checking whether the following equation holds:

\[
\mathcal{A}^{\text{nw}_{1:b}} \leftrightarrow \text{nw}_{1:b} x \times g \pmod{N}
\]  

(6)

Besides, if a new value \( y' \) is added to list, the accumulator value is updated by using the previous accumulator value \( \mathcal{A} \):

\[
\mathcal{A}' = \mathcal{A}'^{y'} \pmod{N}
\]  

(7)

C. Certificate, CRL and Delta CRLs

As we deal with certificates, we would like to also provide some basic background on certificates and their management. Certificates are issued by a CA with a planned lifetime to an expiration date and have unique serial numbers. Once issued, these certificates are valid until their expiration date. However, there are various reasons that cause a certificate to be revoked before the expiration date. These reasons include but not limited to compromise of the corresponding private key, changing the underlying device infrastructure, etc.

Revocation causes each CA regularly issued a signed list called a CRL which is a time-stamped list consisting of serial numbers of revoked certificates and revocation dates. When a PKI-enabled system uses a certificate (for example, for verifying the integrity of a message), that system should not only check the time validity of the certificate, but an additional check is required to determine a certificate’s revocation status during the integrity check. To do so, CRL can be checked to determine the status of the certificate.

There are two main types of CRL: full CRLs and delta CRLs. A full CRL contains the status of all revoked certificates which are not expired yet. Delta CRLs, which is a concept defined in in RFC 5280 \([24]\), contain only the status of newly revoked certificates that have been revoked after the issuance of the last full CRL and before the new release of it. Therefore, a full CRL is issued for a limited time frame and should be updated regularly. Until next update time, delta CRLs help keeping track of the newly revoked certificates. When delta CRLs are enabled, the CA can distribute full CRLs at longer intervals (for reducing distribution overhead) and delta CRLs at shorter intervals. An important point about delta CRL concept is that it does not eliminate the requirement of full CRL distribution. The full CRL must still be re-distributed when the previous full CRL expires since CRL has also a lifetime period as certificates and the lifetime period of delta CRLs are dependent on the lifetime of the previous full CRL. This means both the full CRL and delta CRL should be updated regularly by all the potential nodes that will be using them. In the case of AMI, these CRLs may contain thousand of revoked certificate IDs due to longer expiration dates of issued certificates (even lifelong \([4]\)) and need to be distributed to the each smart meters which will cause a huge overhead due to their size as will be shown in the experiments.

IV. Threat Model

The security of the proposed approach depends on the secure implementation of the revocation management system. Therefore, we considered the following threats to the proposed approach.

1. Compromised certificate attack: In an attacker’s perspective, the meter/gateway is the entry point to the AMI. The attacker can use a compromised certificate to forge a malicious smart meter to connect to the AMI network or impersonate the gateway to apply various attacks.

2. Compromising the accumulator manager: Compromising the accumulator manager that performs accumulator operations could threaten all revocation management. This threat is similar to compromising a CA which requires a new set up from scratch by renewing all accumulator values.

3. Accumulator freshness attack: If an attacker obtains the accumulator value \( \mathcal{A} \) and combines it with the public knowledge of CRL information, he/she can quickly determine which certificates are accumulated in the list. It might lead to deducing the freshness of the accumulator value. As a result, the attacker can perform a chosen attack by using a compromised device which has not been accumulated yet.

4. Stolen non-witness attack: The security of accumulator approach depends on the security of witness/non-witness values. If those values are stolen, an attacker can use those values to authenticate itself to AMI.

V. Proposed Approach

A. Overview

The proposed approach basically eliminates the need to store and distribute CRLs when the devices communicate in a secure manner. Instead of keeping a CRL file for verification of revocation status of certificates, our approach dictates to store at each device (e.g., smart meter, gateway, HES, etc.) only an accumulator value and a proof which proves the validity of the device’s certificate. The accumulator value and proof can be computed at the utility company and distributed to devices in
advantage. Any updates regarding revoked certificates trigger re-computation of these values. Keeping just two integer values for revocation management brings a lot of efficiency in terms of storage and distribution overhead as will be shown in the Experiments section. In the next subsections, we will explain the details of our approach.

B. Adaptation of RSA Accumulator for Our Case

We propose several modifications to the existing RSA Accumulator so that it can be employed in our settings as listed below.

1) Integration of CRL and non-witness Concept: In the traditional CRL approach, when a smart meter presents its certificate to the recipient meter, that meter needs to verify that the presented certificate is NOT in the CRL. To be able to employ the accumulator approach, we generate non-witness values for the presenter to prove that it is not in the list. We accumulate the revocation information (stored in CRLs) into a single accumulator value and produce non-membership witnesses for the non-revoked smart meters.

2) Reducing the Complexity of Accumulator Computation: While computing the accumulator value using Eq. 2 the exponent needs to be computed as \( \prod_{i=1}^{n} y_i \) before doing the modular exponentiation. This becomes infeasible when the size of \( Y \) increases since \( y = \prod_{i=1}^{n} y_i \) will be \( n \times k \) bits assuming each \( y \) is a \( k \)-bit integer. In our approach, we decided to use Euler’s Theorem [25] to cope with this complexity. With access to the totient of \( N \) (i.e., \( \phi(N) \)), the exponent of \( y \) in accumulation computation will be \( u = \prod_{i=1}^{n} y_i \mod \phi(N) \). Thus, with the knowledge of the totient, it becomes more efficient to compute the required values via reducing the \( u \) by \( \phi(N) \).

3) Generating Prime Inputs for the Accumulator: For accumulation, we can use the certificate IDs (\( c_{id} \)) which are generated by the CAs. However, to ensure a collision-free accumulator, we need to use only prime numbers as dictated by the RSA accumulator. Since CRLs contain arbitrary serial numbers for certificate IDs, it is necessary to compute a prime representative for each certificate ID as an input to the RSA accumulator. Thus, we used the random oracle based prime generator described in [22] to generate prime representatives of corresponding newly revoked certificates. The scheme basically has a random oracle \( \Omega() \) function which produces a random function and carries the latest update information to an input to the RSA accumulator. We used the random oracle described in [22] for prime representatives generation from the serial numbers. The scheme basically has a random oracle \( \Omega() \) function which produces a random function and carries the latest update information to an input to the RSA accumulator. We used the random oracle described in [22] for prime representatives generation from the serial numbers. The scheme basically has a random oracle \( \Omega() \) function which produces a random function and carries the latest update information to an input to the RSA accumulator. We used the random oracle described in [22] for prime representatives generation from the serial numbers.

4) Functions of Revocation Management: After preparing the inputs, we compiled and modified the offered accumulator structure and proposed the following functions to construct revocation management for AMI. Our RSA accumulator uses the following input sets: \( \mathbb{Y} \) is the set of prime representatives of revoked certificates’ serial numbers and \( \mathbb{X} \) is set of prime representative of valid certificates’ serial numbers where \( x \in \mathbb{X} \):

- \( \text{aux}_{\text{in}, \text{fo}, N} \leftarrow \text{Setup}(k) \): This function is to set up the parameters of the accumulator. It takes \( k \) as an input which represents the length of the RSA modulus in bits (e.g., 2048, 4096, etc.) and generates modulus \( N \) along with \( \text{aux}_{\text{in}, \text{fo}} \) which is basically Euler’s totient \( \phi(N) \).
- \( A \leftarrow \text{ComputeAcc}(\mathbb{Y}, r_k, \text{aux}_{\text{in}, \text{fo}}) \): This is the actual function which accumulates revocation information by taking prime representatives of serial numbers set \( \mathbb{Y} \). While computing the accumulator value, we propose to use an initial random secret prime number \( r_k \) as a first exponent \((g^{r_k})\) in Eq. 2.
- \( n_{\text{proof}} \leftarrow \text{ComputeNonRevokedProof}(\text{aux}_{\text{in}, \text{fo}}, \mathbb{Y}, x) \): This function first computes a pair of non-witness values represented as \((n_{w1}, n_{w2})\) for a valid certificate whose prime representative is \( x \). Then, the UC concatenates the non-witness value pair with \( x \) and the serial number of the certificate creating a 4-tuple called \( n_{\text{proof}} \).
- \( 0.1 \leftarrow \text{RevocationCheck}(A, n_{\text{proof}}) \): When a smart meter which has a prime representative \( x \) wants to authenticate itself to another party, the other one uses \( n_{\text{proof}} \) and \( A \) to verify that \( x \) is not in the accumulated revocation list by checking Eq. 4.
- \( A^t \leftarrow \text{UpdateAcc}(A^{t-1}, \mathbb{Y}^t) \): This function is for updating the accumulator value \( A \) when the revocation information is updated via deltaCRLs. It takes a set of prime representatives of corresponding newly revoked certificates \( \mathbb{Y}^t \) and latest accumulator value \( A^{t-1} \), and returns the new accumulator value \( A^t \) by utilizing Eq. 7.

Next, we define the components of the proposed framework.

C. Components of Revocation Management System

We propose the system architecture shown in Figure 1 to enable the proposed revocation management and to define its interaction with the deployed AMI components. In addition, the newly introduced components of this architecture and their roles in executing the above defined functions are described below:

- **Smart Meters and Gateway**: The smart meters and gateway can directly communicate with each other and with Head-end System (HES) over LTE. Thus, to ensure the security of applications, these devices need to run the RevocationCheck() function and carry the latest A and the corresponding \( n_{\text{proof}} \).
- **Head-End System**: HES is an interface between the utility operations center and smart meters, and it is located in a demilitarized zone (DMZ). The primary function of the HES is collecting the power data from smart meters and transfer them to head-end management servers (HMS). Since it has two-way communication with smart meters, it

![Fig. 1. The structure of proposed revocation management.](Image)
needs to run the \textit{RevocationCheck()} function and carry
the latest \(A\) and its \(n_{\text{proof}}\).

- **CRL Collector:** The CRL collector plays one of the key
  roles in our revocation management system. It basically
  collects CRLs from various CAs and feeds them to the
  Accumulator Manager. Since it has an open interface to
  the outside network (communicating with other CAs), it
  is placed in DMZ area.

- **Accumulator Manager:** Accumulator Manager is the core
  of our revocation management scheme. It gets CRL
  information from the CRL Collector and accumulates
  them to obtain latest accumulator value. It implements
  the \textit{Setup()}, \textit{ComputeAcc()}, \textit{ComputeNonRevokedProof()},
  \textit{UpdateAcc()}, and \textit{UpdateNonRevokedProof()} functions.
  Whenever a new accumulator value is calculated at a
time \(t\), it sends the accumulator value \(A_t\) and updated
\(n_{\text{proof}}\) to the HMS which then forwards them to HES
for distributing to the smart meters.

- **Head End Management Server:** The collected data is
  managed within HMS. It basically monitors activity logs,
  identifies new devices and manages incident response
  processes. As mentioned, the HMS collects the newly
  generated \(A\) and \(n_{\text{proof}}\) values and sends them to HES
  for distribution.

**D. Revocation and Certificate Verification Processes**

In this section, we describe the proposed revocation scheme
and the protocol for certificate verification.

\textbf{1) Accumulating the CRL:} This process includes two
phases namely the setup phase and the update phase which are
described below.

- **The setup phase:** In this phase of our approach, the
  Accumulator Manager in the UC basically accumulates the
  revoked certificate IDs in \textit{full CRLs}. This process works
  as follows: The \textit{full CRL} files are read, and each certificate
  ID and its issuer’s public key are concatenated to obtain a
  unique string that will be input to the accumulator. Note
  that the issuer’s public key is concatenated on purpose to
  eliminate any duplicates in serial numbers that may come
  from different CAs. Then, the Accumulator Manager
  calculates prime representatives for each concatenated
  string and accumulates these prime representatives to
  obtain the accumulator value. Finally, the Accumulator
  Manager generates non-revoked proofs (i.e., the 4-tuple
  \(n_{\text{proof}}\)) for each end-device (smart meter, gateway, HES,
  etc.) by using \textit{ComputeNonRevokedProof()} function.

- **The update phase:** This phase is for revocation information
  updates that can be done through \textit{delta CRLs}. Due
to such updates, the accumulator value \(A\) and \(n_{\text{proof}}\)
  values should be updated. To update these values, the
  Accumulator Manager first prepares the prime represen-
tatives for the newly revoked certificates (i.e., the ones
  that are included in the \textit{delta CRLs}) by following the
  same approach in the setup phase. It then updates the
  previously computed accumulator value, \(A^{t-1}\), by using
  the \textit{UpdateAcc()} function to obtain \(A^t\) which is then
  used to generate new \(n_{\text{proof}}\) tuples for the end devices
  by using the \textit{UpdateNonRevokedProof()} function.

\textbf{2) Certificate Verification Protocol:} When two meters com-
unicate by sending/receiving signed messages, the signatures in
these messages need to be verified. To be able to start
the verification process, a receiving device needs to use the
public key (for signature verification) presented in the
certificate sent to itself. To ensure that this certificate is not
revoked, then it needs to initiate a process which we call as

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2.png}
\caption{Certificate Verification Protocol Scheme.}
\end{figure}

Our proposed approach addresses all the threats mentioned
in Section \textbf{V.I}. \textbf{Compromised certificate attack:} The
proposed scheme is robust to this type of attack since any revoked
certificate in CRL will be transferred to the smart meters
through \(n_{\text{proof}}\) and \(A\) values. This will prevent authenti-
cation of any revoked devices to the AMI. \textbf{Compromising
the accumulator manager:} First, through the architectural
design in Figure \[1\] the core of our revocation mechanism
(i.e., accumulator manager) is protected from any attacks
by not allowing a direct communication from outside of the
network through two different firewalls. Second, our scheme is
also allowing computation of \(n_{\text{proof}}\) without keeping critical
security parameters of RSA accumulator settings RSA (i.e.,
\textit{aux}, \textit{info}, and \textit{pk}($q$)), since auxiliary data enables a malicious
actor to prove arbitrary statements. These parameters can be
deleted once they are used initially. In such a case, the compu-
tation of \(n_{\text{proof}}\) can still be accomplished, but it may be more
computationally intensive as will be shown in the Experiments
Section. \textbf{Accumulator freshness attack:} While computing
the accumulator value, we use a secret prime number \(r_k\) as a
first exponent ($q^{r_k}$) in Eq. \[2\] This prevents an adversary from
making a guess about accumulated serial numbers. \textbf{Stolen
non-witness attack:} Even if the corresponding non-witness
value \(nw\) of a smart meter is exposed, the authentication
will fail while checking the signatures of the message by the
proposed certificate verification protocol in Fig.\[2].

**VI. Security Analysis**

Our proposed approach addresses all the threats mentioned
in Section \textbf{V.I.} \textbf{Compromised certificate attack:} The
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value \(nw\) of a smart meter is exposed, the authentication
will fail while checking the signatures of the message by the
proposed certificate verification protocol in Fig.\[2].

**VII. Performance Evaluation**

\textbf{A. Experimental Setup}\n
To assess the performance of the proposed approach, we
implemented it in C++ by using FLINT \[26\], which is the
fastest library for number theory and modular arithmetic op-
erations over large integers. For the RSA modulus generation
and prime representatives computation, we used Crypto++
library since it allows thread-safe operations. We prepared
a binary-encoded \textit{full CRL} and \textit{delta CRL} that have been

used for updating both which reflects similar number of hops as in the wild. Unfortunately, ns-3 does not support those frequencies to build bands [28] which helps to reach thousands of smart meters setup in the wild, utilities are able to use 900MHz frequency bands [6 and for 196 setup average hop count is 9). In a typical AMI grid topologies that consist of 81 and 196 smart meters. Even though the number of smart meters in our simulation setup is less than a real AMI setup, it still represents a practical setup in terms of the number of hops due to limited transmission range of 802.11g which leads to multiple hops to reach a smart meter from the gateway (e.g., for 81 nodes the average hop count is 6 and for 196 setup average hop count is 9). In a typical AMI setup in the wild, utilities are able to use 900MHz frequency bands [28] which helps to reach thousands of smart meters through a few hops due to the extended transmission range. Unfortunately, ns-3 does not support those frequencies to build a mesh network, and thus we created a simulation environment which reflects similar number of hops as in the wild.

For communication overhead assessment, we used the well-known ns-3 simulator [27] which has a built-in implementation of IEEE 802.11s mesh network standard. The underlying MAC protocol used was 802.11g. We created two different AMI grid topologies that consist of 81 and 196 smart meters. Even though the number of smart meters in our simulation setup is less than a real AMI setup, it still represents a practical setup in terms of the number of hops due to limited transmission range.

Finally, for more realistic results, we built an IEEE 802.11s-based mesh network comprised of 18 Protronix Wi-Fi dongles attached to Raspberry-Pis which are integrated with the in-house meters as shown in Fig. 3a. While building the testbed on the third floor in the Engineering Center of FIU, we carefully dispersed the meters on the floor as shown in Fig. 3b. To obtain the shown multi-hop routing structure among meters, we decreased the Tx-Power up to by a factor of 16 to limit their transmission range [29]. By such positioning and increased Tx-Power, we strive to mimic realistic conditions that reflect multi-hop routing in a real AMI setup.

B. Baselines and Performance Metrics

We investigated the communication and computation overhead of our approach by using the following metrics:

- **Completion Time**: This metric is defined for communication overhead assessment, which indicates the total elapsed time to complete the distribution of accumulator value and non-revoked proofs to the smart meters from the HES. This metric hints on the communication overhead of revocation management in terms of assessing how it keeps the communication channels busy which are critical for carrying other information.

- **Computation Time**: This is the metric to measure the total time for completing the required computations such as computation of accumulator value, prime representatives, and revocation check time, etc.

- **Storage**: This metric indicates the amount of space for storing the CRL information in the meters.

For comparison to our approach, we used two other baselines from the literature:

- **Traditional CRL Method**: Each smart meter keeps the whole CRL [13] locally which is distributed by the UC.

- **Bloom Filter Method**: A Bloom filter [12] is used to store revoked certificates information. Note that, we employed murmur hash function, which is a non-cryptographic hash function suitable for fast hash-based lookup, to build this Bloom filter. In this case, the Bloom Filter is distributed to each meter by the UC.

C. Communication Overhead

As the main objective of our work was to improve the efficiency of the distribution of the CRLs, we first conducted the communication related experiments to assess the performance of our approach.

1) **CRL Distribution Overhead**: In this subsection, we report on the completion time for the CRL distribution of our approach with respect to other baselines both in simulation and testbed environments. The results which are shown in Fig. 4 indicate the accumulator approach significantly reduces the completion time compared to local CRL and bloom filter approaches due to condensed accumulating. Even with respect to Bloom filter, which is touted as one of the most efficient methods in the literature, our approach reduced the completion time in approximately more than 10 orders of magnitude.

Another critical observation from the simulation results is the scalability capabilities of our approach. While especially for the local CRL approach, the completion time increases significantly, this is not the case for our approach. This can be attributed to the fact that the accumulator value is independent of the revoked CRL size while the overhead of other methods is proportional to the CRL size.

The main overhead of our approach is directly related to the accumulator setting which was 2048 bits in our case. Therefore, even for very large-scale deployments that can have millions of meters, the overhead will not be impacted. In analyzing the experiments results for the testbed, we observe that the completion time takes more time even though the network size is much smaller. This is mainly because of the signal propagation issues such as path attenuation, refraction, interference from other devices, etc. within the building which does not exist in ns-3 simulations. Such issues cause more errors and packet loss and thus increase the re-transmissions to complete all packet distributions. In fact, the AMI infrastructure might have a similar challenge depending on the geographical location (e.g., urban vs rural environments) and thus the distribution of CRL will become even more critical. Therefore, our approach will be more suitable for such environments to reduce the impact from the wild.

2) **CRL Update Overhead**: In this subsection, we conducted experiments to assess the overhead of CRL updates assuming that such updates are done regularly using the delta CRL concept. Fig. 5 shows revocation update overhead in terms of the completion time. As in
the case of full CRL, our approach significantly outperforms others due to the size of the delta CRL. However, the results for the Bloom filter approach shows a different trend this time. It performs worse than the local CRL approach. This can be explained as follows: For each updated revocation information, the Bloom filters must be created from scratch to carry both previous and newly revoked certificates. As a result, updating the CRL will take slightly more time than the whole CRL distribution for Bloom filter and thus will take more time than the local CRL approach. Note that the overhead of CRL distribution is proportional to the size of the delta CRL and thus the completion time follows a similar trend with the results in Fig. 6.

For the testbed results, we observe a similar which consistent with the simulations. Again, the completion time is more due to signal propagation and interference issues.

D. Computation Overhead

We have demonstrated in the previous subsection that our approach significantly reduces the communication overhead. But, we need to also assess whether such a reduction introduces any major computational overhead. Thus, in this subsection, we investigated a detailed computational overhead of our approach. Specifically, we conducted two types of experiments: 1) We assessed the overhead of the computations due to the accumulation process in the Accumulator Manager. These experiments were conducted on a computer which has 64-bit 2.2GHz CPU with 10 hardware cores, and 32 GB of RAM assuming that these are reasonable assumptions for the computer that will act as the Accumulator Manager. Moreover, we also investigated whether some of these computations can be parallelized to further reduce the computation times through multi-thread implementations, and 2) We assessed the computation time for the RevocationCheck() function in meters by implementing it in a Raspberry Pi (smart meter).

1) Overhead Results for the Accumulator Manager: In this subsection, we present and discuss the overhead at the Accumulator Manager by considering the functions below:

Computing Prime Representatives: To assess the computational overhead of prime representative generation, we computed prime representatives for different set sizes. Note that since both the valid and revoked certificates serial numbers are used in our approach, the input size can become huge when AMI scales. Therefore, we also conducted a benchmark test by using threads to show the parallelization ability of our approach. The results are shown in Fig. 6. As can be seen, the computational complexity of the prime representative generation is not overwhelming, $10^5$ representatives can be computed nearly in 1 minute even using a single core. Parallelization reduces the computational complexity by roughly 10 folds which allows computational times in the order of seconds.

Computing the Accumulator Value: Next, we benchmark the computation cost of accumulator value according to different CRL sizes as used in the previous experiment. In addition, we also conducted tests to assess the computational difference between our setting (i.e., the Accumulator Manager has all aux info) and the case where the Accumulator Manager does not have aux info as discussed in Section IV.C.

Note that for the computation of the accumulator value, a parallel implementation was not possible since each step in the computation depends on the previous operation. As seen in Fig. 7, the accumulator value is calculated under a minute for $10^5$ revoked certificates even without using aux info. However, the availability of aux info significantly reduces the computation time making it possible to finish it milliseconds regardless of the size of the CRL.

Computing Non-Revoked Values: Finally, we assessed the overhead of the computation of non-revoked proofs for both the first setup phase by using full CRL and the update phase by using delta CRL. Again, we conducted tests based on the availability/lack of aux info and parallelization ability. Fig. 8 shows the computation overhead of this function according to different AMI sizes. As seen, aux info makes a significant difference in this case. Even with parallelization, the computational times are still in the order of days which may not be acceptable in an AMI setting. The results indicate that aux info needs to be available for efficient computations. We repeated the same experiment for the UpdateNonRevokedProof() function and observed the same trends since the only change was the size of the CRL (i.e., delta CRL is much smaller). These results were not shown due to space constraints.

2) Overhead Results for Revocation Check: Finally, we looked at the computational time overhead for checking whether a certificate is revoked or not based on the three approaches compared. This is an important experiment to understand the computation overhead of our approach on the smart meter, considering the fact that it has limited resources. As can be seen in Table I the elapsed time for a single revocation check is around 10 milliseconds in our approach. Comparing with the other methods, the Bloom Filter has the
best results as expected because it enables faster checking by efficient hash operations. However, Bloom filter suffers from false-positives which degrades its efficiency by requiring access to the server. Our approach does not have such a problem. While our approach doubles the revocation check time compared to the local CRL method, the time is still pretty fast as it is in the order of milliseconds which does not impact any other operation. This is a negligible overhead given that it brings a considerable space-saving benefit which affects both distribution and storage overhead.

| TABLE I | ELAPSED REVOCATION CHECK TIME |
|---------|--------------------------------|
| Local CRL | Bloom Filter | Accumulator Approach |
| Average Time (ms) | 4.1 | 0.06 | 9.8 |

E. Storage Overhead

To compare the storage requirements, we identified the needed revocation information size for our approach and compared it with the other approaches, as shown in [11]. As expected, accumulator has a superior advantage since smart meters just need to store a small accumulator value and non-revoked proof value. Local CRL, on the other hand, keeps the whole CRL list and depending on the number of revoked certificates, it can be huge. For our scenario, the CRL size is around 0.7MB for 30K revoked certificates. While Bloom filter’s performance is also promising, it is still not better than our approach and it suffers from false positives as discussed.

| TABLE II | CRL STORAGE OVERHEAD |
|---------|----------------------|
| Local CRL | Bloom Filter | Accumulator Approach |
| Required Space (MB) | 0.690 | 0.046 | 0.001 |

VIII. CONCLUSION

Considering the overhead of certificate and CRL management in AMI networks, in this paper, we proposed a one-way cryptographic accumulator based approach for maintaining and distributing the revocation information. The framework condenses the CRLs into a short accumulator value and builds a secure, efficient and lightweight revocation mechanism in terms of communication overhead. The approach is inspired from cryptographic accumulators and adopted based on the requirements of AMI. The experiment results indicate that the proposed approach can reduce the distribution completion time significantly for compared to CRL and Bloom filter approaches while introducing only minor additional computational overhead which is handled by the UC. There is no overhead imposed to smart meters.

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