# QEVSEC: Quick Electric Vehicle SEcure Charging via Dynamic Wireless Power Transfer

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Abstract-Dynamic Wireless Power Transfer (DWPT) can be used for on-demand recharging of Electric Vehicles (EV) while driving. However, DWPT raises numerous security and privacy concerns. Recently, researchers demonstrated that DWPT systems are vulnerable to adversarial attacks. In an EV charging scenario, an attacker can prevent the authorized customer from charging, obtain a free charge by billing a victim user and track a target vehicle. State-of-the-art authentication schemes relying on centralized solutions are either vulnerable to various attacks or have high computational complexity, making them unsuitable for a dynamic scenario. In this paper, we propose **Ouick Electric Vehicle SEcure Charging (OEVSEC)**, a novel. secure, and efficient authentication protocol for the dynamic charging of EVs. Our idea for QEVSEC originates from multiple vulnerabilities we found in the state-of-the-art protocol that allows tracking of user activity and is susceptible to replay attacks. Based on these observations, the proposed protocol solves these issues and achieves lower computational complexity by using only primitive cryptographic operations in a very short message exchange. QEVSEC provides scalability and a reduced cost in each iteration, thus lowering the impact on the power needed from the grid.

*Index Terms*—Electric vehicle, authentication, security, privacy, wireless power transfer.

## I. INTRODUCTION

Many countries across the globe are pushing for a transition from fossil-fueled combustion engines to Electric Vehicles (EV), as gas-powered cars are one of the largest sources of greenhouse gases [1]. As battery-powered electric motors replace combustion engines in EVs, there is demand for a power supply solution to periodically recharge their battery.

Dynamic Wireless Power Transfer (DWPT) [2] is a novel technology that enables charging the EV while driving. Dynamic charging systems provide EV owners with the flexibility to charge while moving with the help of Charging Pads (CP), i.e., DWPT base stations embedded under the roads

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providing power to EVs. However, such systems come with novel security and privacy threats, all of which are eased by the use of wireless communications for DWPT and have been proven to be critical in attack scenarios [3].

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Over the past decade, researchers have developed several privacy-preserving authentication schemes for DWPT systems. The authentication protocol needs to be lightweight in terms of communication and computation time, secure against different types of attacks, and preserve the privacy of the user.

Hussain *et al.* [4], [5] introduced the idea of CPs connected to the Charging Service Provider Authority (CSPA) and the hash chain-based authentication and revocation of credentials to avoid the fraudulent use of the same. In this protocol, the EV exchanges multiple messages with the CPs, which are directly connected to the CSPA. This leads to a large number of interactions between the CP and CSPA as well as increased utilization of the CP in the authentication scheme.

Two other works published by Zhao *et al.* [6] and Rabieh *et al.* [7] propose authentication schemes for a similar system model. The former uses public-key encryption with a signing and verification scheme provided by a Registration Authority (RA), and a bank in charge of the token provisioning for the charging requests. Each energy segment transmits a constant amount of energy to the EV.

The latter scheme [7] is based on blind signatures, hash chains, and XOR operations. Additionally, the authors address the double-spending attack, in which a malevolent user tries to abuse old credentials to get a free charge. Several other protocols employing multiple entities such as Cloud Servers (CS), Fog Servers (FS), Pad Owners (PO), and Road-Side Units (RSU) have been proposed [8]–[11]. However, all these approaches consider a decentralized infrastructure involving multiple mutual authentications between the EV and various other entities of the DWPT system. Such exchanges impose higher communication and computational cost on the EV, hence we focus on centralized systems. Therefore, we consider

a simple model that reduces the attack surface and is likely to be maintained in case of advancement of DWPT technology.

In this paper, we propose Quick Electric Vehicle SEcure Charging (QEVSEC), a novel, secure, and efficient authentication scheme with enhancements to the vulnerabilities and inefficiencies of the state-of-the-art protocols. Our protocol originates from vulnerabilities we identified in the existing protocol scheme [4], where an attacker can jeopardize the users' location privacy through the charging process and perform a replay attack due to faulty implementation of hash chains. QEVSEC reduces the number of secrets shared between EV and CSPA to a single one. Thanks to the use of XOR operations, hash functions, and avoiding key-based encryption, we reduce the complexity of the overall authentication process. Our contributions can be summarized as follows:

- We develop a new, secure, and efficient protocol, QEVSEC, that effectively uses exclusive OR operations, hashing, and hash chains.
- We demonstrate both via formal analysis and via the Scyther tool, the security of QEVSEC.
- Compared to the state-of-the-art solutions, QEVSEC improves the performance during authentication in terms of computation time of around 90% with a lower linear increment.

Our paper is structured as follows: Section II presents the model used in the proposed scheme. Section III presents the drawbacks of our reference state-of-the-art protocol. In Section IV, we describe our solution and improvements, providing the security and performance analysis in Section V. In Section VI we draw our conclusions.

## II. SYSTEM AND ADVERSARY MODEL

We briefly describe the system model in Section II.A, and the adversary model in Section II.B.

## A. System Model

We consider four different entities: EV, CP, CSPA, and RA. In our model, the CSPA is directly connected via a wired connection to the RA and all the CPs. The schematic model of the network architecture has been presented in Fig. 1. EV and CPs can directly communicate and authenticate each another, whereas the CSPA can be involved or not, depending on the protocol scheme. The EV contains an On-Board Unit (OBU) that manages the cryptographic operations and securely stores the EV's parameters, including the EV identity and its pseudonyms. We consider the OBU to be secure and tamperproof. The RA is responsible for publishing the parameters for the encryption scheme and generating the pseudonyms for the OBU at the time of registration. The communication between the different facilities and the OBU may either happen through Dedicated Short-Range Communication (DSRC) or other wireless communication protocols.

### B. Adversary Model

Our system considers both the EV and the CSPA as malicious and not trustworthy. The adversary can compose, replay,

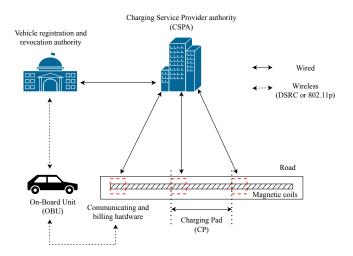


Fig. 1. Our considered system model, that involves the OBU, RA, CSPA, and CPs. The beginning part of these last is a short segment dedicated to communication and computation hardware (indicated with red boxes) that performs all the cryptographic operations.

intercept, and forge messages, but they cannot decipher the message without the correct cryptographic keys. The goal of the attacker is to infer the private key between the two entities to obtain all the parameters of the charging process or to intercept and replay packets to trigger some action by EV or CSPA. Successively, they can launch attacks to get a free charge or identify the vehicle, mining the privacy of the customer. Only the RA is trustworthy and knows the true identity of the EVs, which is never revealed during the authentication process. Because of the symmetric key encryption, the wired communication network is considered secure; however, an adversary can connect to the network and sniff the traffic. If the protocol is poorly designed, an adversary may infer information for further attacks, such as tracing or replay attacks. This adversary representation is formulated in the Dolev-Yao model [12].

#### **III. VULNERABILITIES AND ATTACKS**

In this section, the problems identified in the reference protocol [4] is described. The first challenge is related to the use of the same identifier throughout multiple authentication runs, which can expose the customer's identity and allow tracking of it in different charging processes. This poses a severe threat to the DWPT system privacy, as it will enable tracing the location of the customer by looking at her interaction with the system.

The second research challenge is related to the hash-chain approach  $h^n(x) \rightarrow h(h^{n-1}(x))$  used for OBU-CP authentication, and particularly how the CSPA updates the value for the next expected hash chain value x for a hash function h. Instead of storing the current value received from the OBU (i.e.,  $h^{n-1}(x)$ ), the CSPA in [4] stores the hash value that is already in memory, resulting in the same hash chain parameter received at the beginning of the protocol being stored at each iteration:

$$h(h^{n-1}(x)) = h^n(x).$$
 (1)

This behavior has two consequences. First, the OBU currently participating in the protocol exchange is unable to authenticate itself further. This occurs because the hash value that the OBU sends (e.g.,  $h^{n-2}(x)$ ) and the value that CP or CSPA expects (e.g.,  $h^{n-1}(x)$ ) are different. Following the initial successful authentication, the CSPA repeatedly waits for the same value, resulting in an error. Second, the OBU could send the same  $h^{n-1}()$  value for authentication indefinitely, and an attacker could eavesdrop on the packet and then pose as the authenticated vehicle. Thus, this can result in a successful free-riding attack (i.e., get a free charge by billing another customer) through a replay attack.

To mitigate this vulnerability, it is sufficient to store the most recent value received from OBU, i.e.,

$$h^{i}(PS^{i}_{OBU}) \rightarrow h^{i-1}(PS^{i}_{OBU}).$$
 (2)  
IV. OEVSEC

In this section, we present our protocol QEVSEC. Due to space constraints, we do not reintroduce the protocol in [4]. We point the reader to [4] to grasp the differences between the original protocol and our proposal.

The first step is to provide a way to verify the veracity of the OBU registration later in the scheme. We allow it by storing a copy of the RA database of vehicle pseudonyms with the pairs  $(X_{OBU}, z_i)$  at CSPA, with  $z_i$  being a different random number associated with each  $X_{OBU}$ . We define the value of  $X_{OBU}$  as  $h_2(PS_{OBU}^i)$ , where  $h_2$  is a collision-free hash function provided by RA at scheme initialization, and  $PS_{OBU}^i$  is the pseudonym that CSPA generates for the vehicle. In this way, we generate secrets between CSPA and OBU without revealing the mapping between pseudonyms. The random values are distributed to OBUs along with the corresponding  $PS_{OBU}^i$ , in order to provide a common secret at the beginning of the authentication. Each vehicle has different  $PS_{OBU}^i$  in order to use them for different charging sessions. In fact, a vehicle never utilizes the same  $PS^i$  value more than once.

Following the initialization phase, in the first step EV sends to CSPA the message

$$OBU \to CSPA : m_1 = (X_{OBU}^i).$$
 (3)

CSPA, after receiving the message, constructs the three parameters  $H_1 = h(s \parallel X_{OBU}^i)$ ,  $H_2 = h(H_1) \oplus z_i$ , and  $H_3 = MSK_i \oplus H_1$ , where s is a secret only known by RA, and  $MSK_i$  is *i*-th RA's secret key to use with each different vehicle.  $H_1$  is stored as a security parameter, and CSPA sends only the other two values along with the hash function and a check parameter  $check = h(X_{OBU}^i \oplus z_i)$  in

$$CSPA \rightarrow OBU : m_2 = (h(), H_2, H_3, check).$$
(4)

In this way, the OBU can verify the knowledge of the correct  $z_i$  from CSPA. To avoid overhead message authentication between EV and CP that generates expensive operations in

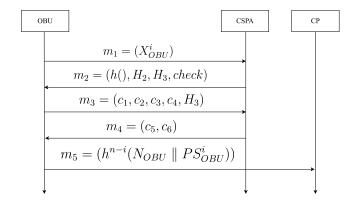


Fig. 2. Diagram scheme of QEVSEC protocol. After  $m_5$ , the OBU sends to the next CP the subsequent value in the hash-chain for authentication.

constrained devices, all the  $m_1$  to  $m_4$  message exchange occurs between the OBU and the CSPA. As a result, OBU mutually authenticates with the system's first level (the CSPA), and then it uses a hash chain to authenticate with the CPs. Therefore, we continue with the following messages to verify the common secret:

$$OBU \to CSPA : m_3 = (c_1, c_2, c_3, c_4, H_3),$$
 (5)

where

$$c_{1} = h(H_{2}) \oplus PS_{OBU}^{i}, c_{2} = h(h(PS_{OBU}^{i}) \parallel H_{3}), \quad (6)$$
  

$$c_{3} = r_{OBU} \oplus PS_{OBU}^{i}, c_{4} = h^{n}(N_{OBU} \parallel PS_{OBU}^{i}) \oplus z_{i}.$$
(7)

In particular, in  $c_1$  the value of  $h(H_2)$  is hidden with the exclusive OR so that CSPA can verify it using the right pseudonym. We use  $c_2 = h(h(PS_{OBU}^i) \parallel H_3)$  to check if the received message is correct and from the right source. In  $c_3$ , the exclusive OR between  $PS_{OBU}^i$  and  $r_{OBU}$  is utilized, with r being a random number. OBU generates a nonce  $N_{OBU}$ in order to generate the hash chain as  $h^n(N_{OBU} \parallel PS_{OBU}^i)$ , sent hidden by the exclusive OR operation with the common secret in  $c_4$ . In this way, the values of  $H_2$  (hidden in the XOR operation) and  $H_3$  (constructed by values known only by CSPA) can be sent in clear at the beginning of the protocol without leaking information that can be used for a Man-In-The-Middle attack. CSPA can use the value of  $H_1$  extracted from  $H_3$  as in the original work [4], and consequently extract  $PS_{OBU}^{i}$  from  $c_1$ ,  $r_{OBU}$  from  $c_3$  and compare the results to  $c_2$ . The hash chain extracted from  $c_4$  is used as an authentication parameter between OBU and each successive CP during the charging process. In the last step of EV-CSPA authentication, similar to  $r_{OBU}$ , CSPA generates a nonce for the run of the protocol,  $r_{CSPA}$ . CSPA sends the following to OBU:

$$CSPA \to OBU : m_4 = (c_5, c_6). \tag{8}$$

where

$$c_5 = P \oplus r_{CSPA},\tag{9}$$

$$c_6 = q^{(P \oplus (r_{CSPA} - n))},\tag{10}$$

$$P = h(r_{OBU} \parallel PS_{OBU}^i). \tag{11}$$

From this message, OBU can extract the value of  $r_{CSPA}$ and check the result of the exponentiation against  $c_4$ . This approach necessitates the publication of the parameters g and n, which are constant during the entire protocol. In the next phase, the CSPA sends the hash chain value provided by OBU to the CPs to authenticate and begin the charging process as in the *hash chain-based authentication* proposed in [4]. Fig. 2 shows our protocol diagram with the message exchange.

#### V. SECURITY AND PERFORMANCE ANALYSIS

In this section, we first prove the security of QEVSEC using BAN Logic [13] and Scyther tool and then compare it with the state-of-the-art in terms of communication costs.

BAN logic uses the concept of *belief*, where the entities involved trust the state of the protocol in terms of *freshness* and *shared secrets*. The former indicates messages sent and received with a nonce or new terms that implicate the freshness of a later packet. The latter is based on two or more parties sharing a valid secret that, if not leaked, indicates that one of the two trusted parties sent a message with this term. The final result of the procedure is a state where both entities involved trust the messages and secrets inside them, without leaking information to third parties. Table I describes the constructs used to prove the security and usability of QEVSEC.

TABLE I BAN CONSTRUCTS FOR THE PROOF.

Notation	Description			
P  = X	P believes X so P thinks that X is true.			
P <  X	P sees message X.			
$ P  \sim X$	P once said X.			
#(X)	X is fresh.			
P = X = Q	X is a secret known only by P and Q			
Shared Key Rule	$\frac{P =Q<-K->P,P< \{x\}K}{P =Q \sim X}$ If P believes that K is a good K and P sees X encrypted with K, then P believes that Q once said X.			
Nonce Verification Rule	$\frac{P =\#(X),P =Q \sim X}{P =Q =X}$ , the only formula in order to promote $ \sim$ to $ =$ , says that P believes X to be recent, and Q said X, then P believes that Q believes X.			
Freshness Rule	$\frac{P =\#(X)}{P =\#(X,Y)}$ , if part of the formula is fresh, the entire formula is believed to be fresh.			

We start by showing that the first two messages  $m_1$  and  $m_2$  allow for a secure exchange, without letting an attacker infer data or get an advantage in replaying the packets. When sending  $m_1$  CSPA $|\#X_{OBU}^i$ , i.e., the provider recognizes  $X_{OBU}^i$  as a fresh parameter, assuming that it was never used by EV or revoked. After  $m_2$  is sent, we can affirm  $EV < |(H_2, H_3, check))$ , and the expressions follow the

rules, in order, *Shared secret rule*, *Freshness rule*, and *nonce* verification rule, i.e.,

$$\frac{EV| = \text{CSPA} = z_i = EV, EV < |check|}{EV| = \text{CSPA}| \sim (H_2, H_3, check)},$$
(12)

$$\frac{EV| = \#(check)}{EV| = \#(H_2, H_3, check)},$$
(13)

$$\frac{EV| = \#(H_2), EV| = \text{CSPA}| \sim (H_2, H_3, check)}{EV| = \text{CSPA}| = (H_2, H_3, check)}.$$
 (14)

From now on, the three rules are used in the same sequence for messages  $m_3$  and  $m_4$ .

Following the above statements, EV, recognizing the freshness of the message received by CSPA, *believes* the other entity with the packet received  $EV| = CSPA| \sim (H_2, H_3, check), EV| = CSPA| = (H_2, H_3, check).$  Similarly, for the parameters in message  $m_3$ ,  $CSPA| = EV| \sim (c1, c'_3, c'_4, c'_5, H_3)$ , i.e., CSPA believes in the packet sent by EV thanks to the extraction of  $H_1$  from  $H_3$  and the retrieval of  $PS_{OBU}^i$ :

$$\frac{\text{CSPA}| = EV = h(h(PS_{\text{OBU}}^i)) = \text{CSPA}, \text{CSPA} < |PS_{\text{OBU}}^i|}{\text{CSPA}| = EV| \sim (c1, c'_3, c'_4, c'_5, H_3)}$$
(15)

$$\frac{\text{CSPA}| = \#(PS_{\text{OBU}}^i)}{\text{CSPA}| = \#(c1, c', c', c', H_c)},$$
(16)

$$\frac{\text{CSPA}| = \#(\text{CI}, c_3, c_4, c_5, H_3)}{\text{CSPA}| = EV| \sim (c1, c_3, c_4, c_5, H_3)}$$

$$\frac{\text{CSPA}| = \#(PS_{\text{OBU}}^i), \text{CSPA}| = EV| \sim (c1, c_3, c_4, c_5, H_3)}{\text{CSPA}| = EV| = (c1, c_3, c_4, c_5, H_3)}.$$
(17)

As before, we show that CSPA believes the parameters retrieved by this last message, considering that it trusts the secrecy of  $z_i$ , i.e.,  $CSPA| = EV| \sim PS_{OBU}^i, CSPA| = EV| = PS_{OBU}^i, CSPA| = EV = PS_{OBU}^i = CSPA$ . Generally, the entire  $m_3$  is trusted, including the nonce  $r_{OBU}$ . With the last message, we can conclude that

$$\frac{EV| = \text{CSPA} = P' = EV, EV < |(c'_6, c'_7)}{EV| = \text{CSPA}| \sim (c'_6, c'_7)},$$
 (18)

$$\frac{EV| = \#P'}{EV| = \#(c'_6, c'_7)},$$
(19)

$$\frac{EV| = \#P', EV| = \text{CSPA}| \sim (c'_6, c'_7)}{EV| = \text{CSPA}| = (c'_6, c'_7)}.$$
(20)

	Scyther results : verify ×						
Claim				Status	Comments		
enhanced	OBU	enhanced,OBU1	Secret PS	Ok	No attacks within bounds		
		enhanced,OBU2	Secret chain	Ok	No attacks within bounds		
		enhanced,OBU3	Niagree	Ok	No attacks within bounds		
		enhanced,OBU4	Nisynch	Ok	No attacks within bounds		
	CSPA	enhanced,CSPA1	Niagree	Ok	No attacks within bounds		
		enhanced,CSPA2	Nisynch	Ok	No attacks within bounds		
Done.							

Fig. 3. Scyther tool results for secrecy of  $PS_{OBU}^i$  and the hash-chain head. The outcomes prove the impossibility of inferring and stealing private information during different protocol runs.

 TABLE II

 COMPUTATIONAL COST COMPARISON BETWEEN QEVSEC AND THE MOST RELATED STATE-OF-THE-ART APPROACHES.

	Auth. OBU [ms]	Auth. CP/CSPA [ms]	Hash-chain [ms]	Total time [ms]
Hussain et al. [4]	$6T_h + 6T_{XOR} = 1.62$	$7T_h + 6T_{XOR} = 1.89$	_	$3.51 \times n$
Rabieh et al. [7]	$4T_{exp} + 4T_{ecm} + 2T_{ver} +$	$2T_{pair}$ + $4T_{ecm}$ + $4T_{exp}$ +	$n \times 0.27$	$20.02 + T_{Hash-chain}$
	$T_{sig} + T_h = 10.01$	$T_{sig} + T_{ver} = 10.01$		
<b>Zhao</b> et al. [6]	$2T_{sig} + 2T_{ver} + T_h = 5.15$	$T_{sig} + 2T_{ver} = 3.89$	$n \times 0.27 + n \times (T_{sig} + T_{ver})$	$9.04 + T_{Hash-chain}$
QEVSEC	$6T_{h} + 5T_{XOR} + T_{exp} =$	$8T_h + 5T_{XOR} + T_{exp} =$	$\mathbf{n}  imes 0.27$	$4.00+\mathrm{T}_{\mathrm{Hash-chain}}$
	1.73	2.27		

TABLE IIICRYPTOGRAPHIC PRIMITIVE EXECUTION TIME.

Primitive	Average Time (ms)
$T_{exp}$	0.110
$T_{pair}$	0.884
$T_h$	0.27
$T_{ecm}$	1.352
$T_{ver}$	1.449
$T_{sig}$	0.992

Finally, EV recognizes the validity of CSPA, with the secrecy and freshness of the different parameters involved during the authentication, including nonce  $r_{\text{CSPA}}$ , i.e.,  $EV| = \text{CSPA}| \sim (c'_6, c'_7), EV| = \text{CSPA} = P' = EV, EV| = \text{CSPA}| = (c'_6, c'_7)$ . This concludes the proof for the impossibility of performing a replay attack.

To further prove the security of QEVSEC, we test it with Scyther tool [14], a program used to inspect a cryptographic protocol in order to find possible attacks. Fig. 3 shows the results of the tool, proving the security of the most important parameters in the scheme. QEVSEC is secure in different consecutive runs, maintaining the secrecy of the different parameters for the EV.

To conclude the analysis, a comparison is provided by counting the number of operations in the authentication steps between OBU-CSPA and OBU-CP. Table III reports the time taken by the operations in the modified scheme, computed using a simulation of the primitives in Python, using Charm-Crypto Library [15]. In order,  $T_{exp}$  and  $T_{pair}$  are the time for exponentiation and pairing, respectively.  $T_h$  is the hash computation time, while  $T_{ecm}$  is the cost for the elliptic curve multiplication. Finally,  $T_{ver}$  and  $T_{sig}$  are the time for signing end verification in [7] and [6]. These time values are used to compare the different protocols with a common basis for the computational cost of the primitive operations. The exclusive or operation consumes little time, and hence, it is excluded in the results. In Table II, we report the cost that each step of authentication takes in time, using "-" when no messages are exchanged in that phase. The total time taken by [4] for a single CP is lower by 0.5 ms with respect to QEVSEC, but this value has to be multiplied for each pad used during the charging process. Considering the integration of the hash chain at the CP level, we achieve better performance after the first constant part of the protocol. Following that, instead of the entire computation cost for the

authentication process, as in [4], we need only a message containing a hash, thus remarkably reducing the overall cost. Our protocol has minimal overhead stemming from the preauthentication message exchange required to eliminate the usage of any parameter that can be used to track user activity. Rabieh *et al.* [7] comprises a digital signature, while in Zhao *et al.* scheme [6], also a digital signature is requested for each plate, making the two schemes computationally heavier than QEVSEC. In Fig. 4, we show the results for the computation time with respect to the number of pads used in the charging process. Our protocol has a lower setup time and the hash chain allows a linearly incremental time that maintains the total time lower than the other protocols.

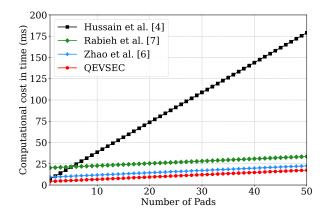


Fig. 4. Computational time against the number of charging pads.

## VI. CONCLUSION

The vulnerabilities we identified in the state-of-the-art allow the adversary to attack the charging infrastructure or EV by eavesdropping, intercepting, and tampering with the exchanged messages. We propose QEVSEC, an enhanced, lightweight, and secure authentication protocol that improves system security by eliminating threats while lowering the computational costs of the system. QEVSEC protects the EV from adversarial attacks including but not limited to replay and denial-of-service attacks. Furthermore, it provides scalability with respect to the number of pads. We also proved the security of our scheme against replay attacks and its secrecy via both formal analysis and an automated tool. Our comparison with other state-of-the-art approaches shows that QEVSEC is the best-performing solution in terms of computational cost.

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