Securing Demand Response Management:  
A Certificate-Based Access Control in Smart Grid Edge Computing Infrastructure  

SHEHZAD ASHRAF CHAUDHRY, HOSAM ALHAKAMI, ABDULLAH BAZ, (Senior Member, IEEE), AND FADI AL-TURJMAN, (Member, IEEE)  

1Department of Computer Engineering, Faculty of Engineering and Architecture, Istanbul Gelisim University, 34310 Istanbul, Turkey  
2Department of Computer Science, College of Computer and Information Systems, Umm Al-Qura University, Makkah 21421, Saudi Arabia  
3Department of Computer Engineering, College of Computer and Information Systems, Umm Al-Qura University, Makkah 21421, Saudi Arabia  
4Artificial Intelligence Department, Near East University, 10 Mersin, Turkey  
5Research Center for AI and IoT, Near East University, 10 Mersin, Turkey  
Corresponding author: Shehzad Ashraf Chaudhry (sashraf@gelisim.edu.tr)  
This work was supported by the Deanship of Scientific Research at Umm Al-Qura University under Grant 18-COM-1-01-0001.  

ABSTRACT  
The edge computing infrastructure has enabled a massive amount of data in the smart grid environment by a large number of connected automated devices to be processed at the edge of the network in proximity to the data generation source. The demand response management is a fundamental requirement for an efficient and reliable smart grid environment, which can be accomplished by the transfer of data between smart devices and the utility center (UC) in a smart city, very frequently. However, this frequent data transfer is subject to multiple threats including the tempering. Several authentication schemes were proposed to secure smart grid environment. However, many such schemes are either insecure or lack the required efficiency. To counter the threats and to provide efficiency, a new authentication scheme for demand response management (DRMAS) is proposed in this paper. DRMAS provides all necessary security requirements and resists known attacks. The proposed DRMAS is provably secure under formal analysis supplemented by a brief discussion on attack resilience. Moreover, the DRMAS completes the authentication procedure in just 20.11 ms by exchanging only 2 messages.  

INDEX TERMS  
Smart grid security, key establishment, device access, certificate, ECC, incorrectness, random oracle model.  

I. INTRODUCTION  
Smart grid (SG) is envisioned to be the next generation power systems providing a seamless integration of cyber physical systems, information and communication technologies (ICT), and power generation and distribution domains. This advanced power grid system provides a bidirectional flow of energy between clients and utility service providers, and as a result the power consumption may be controlled and optimized in accordance with the real-time needs of the customer, which is productive for both customer as well as power generation domains. In comparison with conventional power grid, the SG-based system has advanced sensing and computing devices including sensors, actuators etc., for generating and transmitting the bidirectional flow of power-related real-time information. In SG-based system, there exist various levels of data flow to manage the demand response (DR). The short range communication technologies such as Zigbee, Bluetooth, Infrared, and 6LowPAN constitute the first level of information flow, while medium and long-range wireless communication networks such as LTE/LTE-A, WiMax, WiFi, and cellular networks represent the second level of information flow [1], [2]. These two levels of information flow for respective technology networks provide intelligent communication architecture for bridging the gaps between demand and supply of electric power on real-time basis. A typical smart grid architecture is shown in Fig. 1. It is worthy to note that by utilizing DR the SG may convey the real-time information regarding the ideal price of electricity at regular time intervals (every 10-15 min) to enable the users to adjust
In recent years many authentication protocols for SG environment can be witnessed. In this connection, a key distribution protocol for identity-based signature and encryption has been demonstrated by Odelu et al. [11]. This protocol supports mutual authentication by constructing an agreed session key between smart meters (SMs) and the utility service provider. However, according to Tsai and Lo [12] the scheme proposed in [11] is vulnerable to session specific temporary information threat, and in return may compromise the privacy of SMs on revealing secret credentials. Besides, countering the security drawbacks in [11], the Odelu et al. presented an improved SG-based authentication protocol. Later, Doh et al. [13] designed an authenticated key agreement scheme ensuring mutual authenticity to both participants, SM and UC. Afterwards, Saxena et al. [14] presented a scheme for smart grid systems making certain the security against insider and outsider threats as posed to the SG environment. Later, He et al. [15] presented an elliptic curve cryptography (ECC)-based key distribution protocol for SGs ensuring anonymity to the stakeholders. This scheme has comparatively low computational and communicational overheads in comparison with Tsai and Lo’s scheme [11]. In [16], Ali et al. presented an identity-based key management scheme employing elliptic curve cryptography to enhance the security of smart grid systems. However, Mahmood et al. [17] found that the scheme presented in [16] has serious weaknesses including the exposure of trusted authority’s master key and is prone to many related attacks. Similarly, Mahmood et al. [18] also employed ECC to present a lightweight authenticated key agreement protocol to secure the interaction among clients and substations in the smart grid system. Nevertheless, Abbasinezhad-Mood and Nikooghadam [19] found that [18] does not comply with perfect forward secrecy, and was proved to be susceptible under CK adversarial model. Mahmood et al. presented another scheme [20], the authors in [21] argued that Mahmood et al.’s scheme [20] is vulnerable to ephemeral secret leakage and impersonation attacks. In 2018, another scheme [22] to provide security in SG environment was proposed by Challa et al. However, Chaudhry et al. [23] stated that the scheme [22] is unable to provide authentication between two entities of SG and has some other critical issues. The scheme of Chaudhry et al. [23] requires intervention of third party for establishing a secure connection between two SG devices. In 2019, Kumar et al. [24] proposed yet another temporal credential and ECC based authentication scheme for securing demand response management. However, the inherited incorrectness in their scheme to accommodate only one smart meter may restrict it’s practical deployments and the obvious lack of initial verification on UC side, can encourage an adversary to force UC to process illegal requests [25].

A. MOTIVATIONS AND CONTRIBUTIONS

The SG-based system relies on internet-oriented communication and networking which renders the SG infrastructure vulnerable to several attacks including forgery attacks, impersonation attacks, man-in-the-middle attacks and replay attacks. This strong reliance of deployed smart meters (SMs) on ICT raise the same security concerns as already posed to ICT-based paradigms. These security loopholes may create gaps between demand and supply of power if exploited by malicious intruders. Furthermore, these might lead to misleading forecasting models and findings related to DR management. Thus, there is dire need to restrain the probability of different known threats to provide a smooth flow to smart grid operations in terms of DR and data analytics. Most of the existing schemes for securing DR in SG environments
II. DRMAS: PROPOSED SCHEME

This section explains the proposed DRMAS for securing demand response management in smart grid environments. Proposed DRMAS as depicted in Fig. 2 is detailed as follows:

A. SYSTEM SETUP

To accomplish the setting up of the system, the trusted authority $\mathcal{T}_A$ selects an elliptic curve $E_p(\alpha, \beta)$ over finite field $\mathbb{F}_p$ along with a base point $G = E_p(\alpha, \beta)$ of large order $n$ s.t. $nG = O$ (a point at infinity). The $p$ is selected as a very large prime number satisfying $4a^3 - 27b^2 \neq 0 \mod p$. $\mathcal{T}_A$ then selects $x$ as private and $Q = xG$, as its’ own public key.$\mathcal{T}_A$ also selects a secure one way function $h(\cdot)$ and finally, publishes $\{E_p(\alpha, \beta), G, Q, h(\cdot)\}$.

B. UC REGISTRATION

For registering each $UC_j : [j = 1, 2, . . . n]$, $\mathcal{T}_A$ selects unique $ID_j$, private key $k_{ID_j}$ and computes public key $P_{Uj} = p_{Uj}G$. $\mathcal{T}_A$ finally, stores $\{ID_j, P_{Uj}, G, Q, ID_j : [j = 1, 2, . . . m]\}$, $RJD_j : [j = 1, 2, . . . m]$, $h(\cdot), E_p(\alpha, \beta)$ in the memory of $UC_j$.

C. SG DEVICE REGISTRATION

For registering each $SG$ device $SD_i : [i = 1, 2, . . . m]$, $\mathcal{T}_A$ selects unique $ID_i$ and computes $RJD_i = h(\mathcal{ID}_i || x)$. $\mathcal{T}_A$ then computes certificate parameter $\mathcal{C}_i = x + H(\mathcal{ID}_i || Q) x$. $\mathcal{T}_A$ finally, stores $\{RJD_i, \mathcal{C}_i, E_p(\alpha, \beta), G, Q, P_{Uj} : [j = 1, 2, . . . n]\}$, $h(\cdot)$ in the memory of $SD_i$.

D. AUTHENTICATION

In Proposed DRMAS scheme, $SD_i$ initiates authentication phase to furnish a secure session key with $UC_j$. The steps as illustrated in Fig. 2 and briefed below are performed between $SD$ and $UC_j$ to complete this phase:

PDR 1: $SD_i \rightarrow UC_j : \{m_1\}$
$SD_i$ selects $r_i \in \mathbb{Z}_n^*$ randomly and generates current timestamp $T_1$, $SD_i$ then compute $U_i = r_iG$ and $W_i = r_iP_{Uj} = r_i p_{Uj}G$ along with the timestamp based random certificate $\mathcal{C}_i = r_iT_1 + \mathcal{C}_i = r_iT_1 + x + H(\mathcal{ID}_i || Q)x$. Finally, $SD_i$ computes $H_i = h(U_i || W_i || \mathcal{C}_i || RJD_i || T_1)$, dynamic pseudo identity $\mathcal{ID}_i = ID_i \oplus W_i$ and sends $m_1 = \{\mathcal{ID}_i, H_i, U_i, C_i, T_1\}$ to $UC_j$.

PDR 2: $UC_j \rightarrow SD_i : \{m_2\}$
$UC_j$ after receiving $m_1$, first verifies message freshness by checking $|T_1 - T_1^*| \leq 0$, and upon success $UC_j$ computes $\mathcal{W}_i = r_jU_i$ and $\mathcal{ID}_j = \mathcal{ID}_j \oplus \mathcal{W}_i$. $UC_j$ checks existence of $ID_i$ in verifier database and on success extracts $RJD_i$. $UC_j$ then checks the genuineness of random certificate as $C_iG = T_1U_i + Q + H(\mathcal{ID}_i || Q)Q$ and $H_i = h(U_i || W_i || \mathcal{C}_i || RJD_i || T_1)$, aborts the session, if any of these is invalid. Otherwise, $UC_j$ select $r_j \in \mathbb{Z}_n^*$, $T_2$ and computes $U_j = r_jG$, $W_j = r_j U_i = r_j r_jG$, and session key $\mathcal{K}_{ij} = h(W_i || \mathcal{ID}_i || RJD_i || \mathcal{ID}_j || W_j || T_2)$ along with $H_j = h(\mathcal{K}_{ij} || \mathcal{ID}_i || RJD_i || W_j || T_2)$. $UC_j$ completes this step by sending $m_2 = \{U_j, H_j, T_2\}$ to $SD_i$. 

are either vulnerable to many security threats or suffer from high computation and communication costs; mainly due to underlying pairing based operations. Therefore, we desperately need an authenticated key agreement protocol for SG environment supporting the SG device validation as well as the dynamic addition of Utility Centre (UC). For securing the demand response (DR) management, in this paper, we propose an authentication scheme $\text{DRMAS}$ which can mitigate pitfalls of existing schemes. The research contributions are illustrated as under:

1) A new certificate based authentication scheme $\text{DRMAS}$ is proposed to manage demand response in smart grid-based systems, which makes certain the exchange of sensitive information only after a mutually agreed session key is established between SG device and UC. The proposed scheme is free of any costly pairing based operations and completes authentication by exchanging only two messages.
2) We employed a universally accepted Real-or-Random (ROR) model [26], [27] to formally verify the security features.
3) The informal security analysis of the contributed scheme is also presented to prove the resistance of the scheme against all known attacks.
4) We compare the performance and security features of the proposed $\text{DRMAS}$ and related schemes.

B. THREAT MODEL

We employ the Dolev-Yao threat model [26] in our proposed protocol. Employed in a variety of protocols, [28]–[34], this model assumes an insecure public channel that is used by the communicating participants. Precisely, An adversary $\mathcal{A}$ may take this opportunity to misuse the intercepted communication data, since $\mathcal{A}$ might eavesdrop, replay, alter or delete any data during transmission by acting as an intermediary between the legal parties. Assuming, the smart devices are not tamper resistant, and the adversary could recover the stored contents from SG devices using power analysis attacks [35], [36]. We assume the trust authority (TA) to be fully trusted, and the utility centre (UC) as semi-trusted since both of these entities may not be compromised by the attacker.

---

**TABLE 1. Notation guide.**

| Notations | Description |
|-----------|-------------|
| $SD_i$, $UC_j$, $\mathcal{T}_A$ | SG device, Utility control, Trusted Authority |
| $ID_j$, $ID_i$ | Identities of $SD_i$, $UC_j$ |
| $RT_j$, $RT_i$ | Registration Time-stamps of $SD_i$, $UC_j$ |
| $p$, $Z_p$, $E_p(\alpha, \beta)$ | Large prime, finite field over $p$. Elliptic Curve |
| $G$, $kG$ | A point over $E_p(\alpha, \beta)$, scalar multiplication |
| $x$, $Q = xG$ | $\mathcal{T}_A$’s key pair |
| $P_{\mathcal{A}}$, $P_{\mathcal{U}}$ | Private keys of $SD_i$, $UC_j$ |
| $P_{\mathcal{A}}$, $P_{\mathcal{U}}$ | Public keys of $SD_i$, $UC_j$ |
| $C_k$ | Certificate of $k^{th}$ entity |
| $\mathcal{A}$, $\Delta T$ | Attacker, delay tolerance |
| $T_1$, $T_2$, $T_3$ | Time stamps |
| $\oplus$, $\otimes$ | Concatenation and xor functions |
| $\tilde{=}$, $h(\cdot)$ | Equality Check, Hash function |
E. SG DEVICE DYNAMIC ADDITION

The dynamic addition of a new device SD\textsuperscript{new} requires very similar procedure as of SG device registration. For dynamic addition of a device SD\textsuperscript{new} T.A selects unique ID\textsuperscript{new} and computes RID\textsuperscript{new} = h(ID\textsuperscript{new}||x). T.A further computes certificate parameter \(C_i = r_iT_2 + x + H(ID_i||Q)x\). T.A then stores \{RID\textsuperscript{i}, C\textsubscript{i}, E\textsubscript{p}(\alpha, \beta), G, Q, P\textsubscript{ui} : i = 1, 2, ..., n\}, \(h(\cdot)\) by using power analysis attacks \[35\]–\[37\]. Here, RID\textsubscript{i} = h(ID\textsubscript{i}||x) and \(C\textsubscript{i} = x + H(ID_i||Q)x\). Finally, T.A sends RID\textsuperscript{new} to each UC\textsubscript{j}.

III. DISCUSSION ON FUNCTIONAL SECURITY

This section briefly discusses the functional security of the proposed scheme along with comparison of the security features extended by proposed and related schemes under the realistic adversarial model as mentioned in subsection I-B.

A. REPLAY ATTACK

An adversary A may eavesdrop the authentication request and reply messages, i.e., \(m_1 = \{ID_i, H_i, U_i, C_i, T_1\}\) and \(m_2 = \{U_j, H_j, T_2\}\) between SD\textsuperscript{i} and UC\textsubscript{j} in mutual authentication phase. However, the involvement of timestamps \(T_1\) and \(T_2\) in respective authentication messages \(m_1\) and \(m_2\), refrains the adversary to store and initiate replay attack at some future time. In that case, the legal participants may check the timestamp of message and abort the session, thereafter. Hence, the contributed scheme is protected from replay attack.

B. STOLEN SG DEVICE ATTACK

An adversary may steal or physically compromise the SG device, since these devices are normally deployed in the proximity of home or nearby places. Then the former may recover the critical contents of the SG device, such as \{RID\textsubscript{i}, C\textsubscript{i}, Q, Pu\textsubscript{i} : i = 1, 2, ..., n\}. Using the power analysis attacks \[35\]–\[37\]. Here, RID\textsubscript{i} = h(ID\textsubscript{i}||x) and \(C\textsubscript{i} = x + H(ID_i||Q)x\). Finally, T.A sends RID\textsuperscript{new} to each UC\textsubscript{j}.

C. SG DEVICE IMPERSONATION ATTACK

An adversary may attempt to launch a SG device (SD\textsubscript{i})-impersonation attack by submitting an authentication request message towards UC\textsubscript{j}. For constructing this message, it may
generate a random integer $r_i^A \in Z_p^*$ and a fresh timestamp $T_1$, and then compute $U_i^A = r_i^A G$ and $W_i^A = r_i^A Pu_i$, where $Pu_i$ is the public key of $UC_i$. However, to construction of a valid authentication request $m_1 = \{ID_i, H_i, U_i^A, C_i, T_1\}$ it requires to compute $C_i, H_i$ and $ID_i$, i.e. $C_i = r_i^A T_1 + C_i, H_i = h(U_i||W_i^A||C_i||RID_i||T_1)$ and $ID_i = ID_i \oplus W_i^A$, which is not possible until it gains access to some crucial parameters such as $RID_i$, $C_i$, and $ID_i$. This depicts that the proposed scheme is protected from SG device impersonation attack.

D. MAN-IN-THE-MIDDLE ATTACK
An adversary may attempt to maneuver the intercepted messages by introducing suitable modifications in the message contents to impersonate the legal parties on both ends. In our scheme, the adversary, upon receiving the authentication request $m_1 = \{ID_i, H_i, U_i^A, C_i, T_1\}$ from $SD_i$, may generate a random integer $r_a \in Z_p^*$ and a fresh timestamp $T_a$, and then compute $U_a = r_a G$. However, for constructing a legal authentication request $m_1 = \{ID_i, H_i, U_a, C_i, T_a\}$ it requires to compute a valid parameters, i.e., $C_i, H_i$ and $ID_i$, i.e. $C_i = r_i^A T_1 + C_i, H_i = h(U_a||W_i'||C_i'||RID_i||T_1)$ and $ID_i = ID_i \oplus W_i'$, which is computationally not feasible until the secret credentials $RID_i, C_i,$ and $ID_i$ are accessed. Likewise, $A$ may also attempt to modify the acknowledgment authentication message $m_2 = \{U_j, H_j, T_2\}$ according to fresh timestamp $T_2$. However, the involvement of secret credential $RID_i$ in the calculation of $H_i$ refrains the adversary to construct a fake acknowledgment message. Hence, the contributed scheme is immune to man-in-the-middle attack.

E. UC IMPERSONATION ATTACK
To impersonate as $UC_j$, the adversary needs to construct a valid acknowledgment authentication message $m_2 = \{U_j, H_j, T_2\}$ with current timestamp $T_2$, where $U_i^A = r_i^A G, W_i^A = r_i^A U_i, SK_{ij} = h(W_i^A||U_i^A||RID_i||U_i||W_i||T_2)$, and $H_j = h(SK_{ij}||RID_i||W_i^A||W_i||T_2)$. The adversary may generate a random number $r_j^A$ and fresh timestamp $T_2$, then it may further compute $U_j^A = r_j^A G$, $W_j^A = r_j^A U_i$. Nevertheless, the use of secret credential $RID_i$ debar the adversary to compute $SK_{ij}$ and in return $H_j$, which nullifies the chances of the adversary’s constructing a valid $m_2 = \{U_j, H_j, T_2\}$ message. Thus, our scheme is protected from $UC_j$ impersonation attack.

F. SESSION KEY SECURITY
In authentication phase of proposed model, the session key $SK_{ij}$ is established with secure mutual communication between $SD_i$ and $UC_j$ as $SK_{ij} = h(W_j||U_j||RID_i||U_i||W_i||T_2)$, where $W_j = r_j U_j = r_j G, U_j = r_j G, RID_i, U_i$ and $W_i = pr_j U_i$. It is evident that the strength of computed session key is based upon two constituent factors: 1) temporary secrets $r_i$ and $r_j$, and 2) long term secret parameters such as $pr_j$ and $RID_i$. It is worthy to note that in our protocol, the identities such as $ID_i$ and $ID_j$, and master secret key $x$ of $TA$ are only known to the $TA$. We may consider the following two cases regarding the robustness of session key.

Case 1: In case, the temporary session variables $r_i$ and $r_j$ are revealed to the adversary, the session key $SK_{ij}$ is hard to compute for the adversary due to lacking long term secrets $RID_i$ and $pr_j$.

Case 2: Likewise, in case the long term secret parameters such as $RID_i$ and $pr_j$ are revealed to the adversary, the $SK_{ij}$ still remains hard to compute for the adversary due to lacking temporary session variables $r_i$ and $r_j$. While, these variables $r_i$ and $r_j$ are protected in $U_i$ and $U_j$, respectively, since it is computational hard to recover $r_i$ and $r_j$ from $U_i$ and $U_j$ due to non-breakable security feature of elliptic curve discrete logarithm problem (ECDLP).

If we take the assumptions of both cases combined, i.e. the temporary session variables ($r_i$ and $r_j$) as well as long term secret parameters ($RID_i$ and $pr_j$) are revealed to the adversary, only then the later would be able to compute the legitimate session key. Moreover, if the current session key $SK_{ij}$ as established between the participants, is revealed to the adversary, then the later may not be able to compute the session keys of other sessions between the same parties, since every authentication session bears the unique temporary session variables. Hence, it would be unlikely for the adversary to be able to compute the previous or future session keys from the current revealed session key. In this manner our scheme provides perfect forward as well as backward secrecy to the legal participants.

G. ANONYMITY AND UNTRACEABILITY
In proposed scheme, an adversary may eavesdrop the communication messages $m_1 = \{ID_i, H_i, U_i^A, C_i, T_1\}$ and $m_2 = \{U_j, H_j, T_2\}$ over an insecure channel. However, $A$ might not be able to derive the smart device’s identity $ID_i$ from the exchanged messages, which is one of the crucial requirements in the security of smart grid system for the customer. Moreover, $A$ may also be unable to distinguish the message contents of a session from other sessions either established between the same or different participants. This property ensures that a smart device may not be traced by the adversary. This is because of the fact, the parameters in $m_1$ and $m_2$ messages involve either current timestamps ($T_1$ and $T_2$) or fresh nonces ($r_i$ and $r_j$), respectively.

IV. FORMAL SECURITY ANALYSIS
Over the past few years, the security analysis under formal methods has got popularity and is being considered as the main strong proofing method. The popular Real-Or-Random (OR) [26], [27] model is adopted here to prove the security of propose $DRMAS$. In $DRMAS$, there are three entities of environment, $TA$, $SG$ device $SD_i$ and $UC_j$. In ROR model the following ingredients are described below.

A. PARTICIPANTS
Let $I_{TA}^z, I_{SD}^y,$ and $I_{UC}^x$ be the instances $x, y$ and $z$ of $TA$, $SD_i$ and $UC_j$, which is called oracles.
B. ACCEPTED STATE

I* being an instance is considered as accepted, the accept state is achieved after last message is received during protocol execution. The (sid) of I* is termed as session identifier and is the ordered concatenation of all communication messages (received or sent) for a current session.

C. PARTNERING

Let I*1 and I*2 are known to be partnered, once the following three states are occurred simultaneously.
1) I*1 and I*2 are in accept state.
2) I*1 and I*2 are mutual authenticate and share identical (sid) with each other.
3) Both I*1 and I*2 are mutual partners.

D. FRESHNESS

Both instances I*SD, and I*UC are fresh, if SKij (session key) between SDi and UCi is not exposed to an attacker A using the query \( \mathcal{R}(I^*) \) defined below.

E. ADVERSARY

Following ROR model, A is supposed to fully control all communications and can also use the following defined queries to eavesdrop, modify, manufacture and inject messages [27]:

1) Execute(I*, I*): It is simulated as eavesdropping attack in which after execution of such a query, A can collect the transmitted messages.

2) Reveal(I*): The current session key SKij generated by \( \Pi^* \) (and its partner) is revealed to A on execution of this query.

3) Send(I*, msg): By executing this, A being an active adversary can send msg to I* and can also receive the response.

4) Test(I*, msg): It represents the session key's (SKij) semantic security, under RoR's indistinguishability. A gets SKij from I*, on the successful running of an experiment involving an unbiased coin \( \beta \) flipped before start of the game, the output is known to A only, if SKij is fresh and \( \beta = 1 \). Otherwise, A gets null value.

F. SEMANTIC SECURITY OF THE SESSION KEY

According to the requirements of ROR model, adversary needs to distinguish between an instance’s original session key SKij and a random key. A can allow several test queries to either I*SD or I*UC. Before the game finished, adversary returns the guessed bit \( \beta' \) and A can win the game if condition \( \beta' = \beta \) is matched. If SUC represents an event that adversary can win the game, the advantage \( \text{Adv}_{A}^{\text{AKA}} \) of adversary in breaking the semantic security of the session key SKij in our authenticated key-agreement AKA protocol, say P is represented and defined by \( \text{Adv}_{A}^{\text{AKA}} = |2 \cdot \text{Pr}[SUC] - 1| \).P is said to be secure, \( \text{Adv}_{A}^{\text{AKA}} \leq \psi \), where \( \psi > 0 \) is a small real number.

G. RANDOM ORACLE

The legal entities as well, A can access \( h(\cdot) \), which is simulated as random oracle say HSH [27]. Following definitions are referred to prove the Theorem 1:

**Definition 1:** Let a deterministic function \( h : \{0, 1\}^* \rightarrow \{0, 1\}^* \) is collision resistant, which takes input \( v \in \{0, 1\}^* \) with arbitrary length and produces \( h(v) \in \{0, 1\}^* \) of fixed length [38]. The advantage of \( A \) to find collision is represented and defined by \( \text{Adv}_{A}^{\text{HSH}}(x) = \text{Pr}[b_1 \neq b_2 | h(b_1) = h(b_2)]; \) here, \( \text{Pr}[E] \) (\( b_1 \), \( b_2 \)) \( \rightarrow \) R.A represents the probability of the event \( E \) represent. The the pair \( (b_1, b_2) \) is selected randomly by \( A \).The adversary \( A \)'s advantage to made random choices within limited time bound \( \text{tim} \) is considered. The attack on collision resistance of \( h(\cdot) \) by an \( \psi, \text{tim} \)-adversary is at most \( \text{Adv}_{A}^{\text{HSH}}(\text{tim}) \leq \psi \).

**Definition 2:** Let \( G \in \mathcal{E}(\alpha, \beta) \) is a point and given a quadruple \( (G, r_G, r_G, W_G) \), decide whether \( w = r_G \) or not is termed as the ECDDHP.

**Theorem 1:** Consider a polynomial time (\( \text{tim} \)) bound adversary \( A \) against the introduced DRMAS under ROR model. If \( q_{\text{ECDDHP}} \) and \( \text{hsh} \) denote maximum numeral and range space of HSH queries and \( \text{adv}_{\text{ECDDHP}}(x) \) expresses \( A \)'s advantage to break ECDDHP. The adversary can carry out \( A \) to break semantic security of \( SK_{ij} \) in DRMAS is \( \text{adv}_{\text{DRMAS}}^{\text{AKA}} \leq \frac{q_{\text{ECDDHP}}}{|\text{hsh}|} + 2\text{adv}_{\text{ECDDHP}}(x) \).

The number of HSH queries, the range space of hash function \( h(\cdot) \) and the advantage of \( A \) in breaking the semantic security of the session key \( SK_{ij} \) in \( \mathcal{P} \) is \( \text{adv}_{\text{DRMAS}}^{\text{AKA}} \leq \frac{q_{\text{ECDDHP}}}{|\text{hsh}|} + 2\text{adv}_{\text{ECDDHP}}(x) \).

**Proof:** The proof resembles to the same presented in [24] and [27]. The in-sequences games \( G_i : i = 1, 2, 3, 4 \) are demarcated for the purpose of security analysis. Let \( \text{SUC}_i \) be an event wherein \( A \) can correctly guess random bit \( \beta \) in \( G_i \). Details are as follows:

**Game1** \((G_1)\): \( G_1 \) simulates the actual attack launched by \( A \) against DRMAS under ROR model. Therefore, we have:

\[
\text{Adv}_{\text{DRMAS}}^{\text{AKA}} = |2 \cdot \text{Pr}[G_1] - 1|.
\]

**Game2** \((G_2)\): simulates actual eavesdropping launched by \( A \). The \( A \) can perform a query to \( \text{Execute}(I^*, I^*) \) oracle. To complete \( G_2 \), \( A \) queries the test oracle and result of test can confirm the correctness of \( SK_{ij} \). Note that \( SK_{ij} \) is calculated by both \( SD_i \) and \( UCI_j \) as \( SK_{ij} = h(W_j||U_j||RID_j||ID_j||U_i||W_i||ID_2) \). To calculate session key \( SK_{ij} \) requires pair \( \{y, z\} \) (the ephemeral secrets), and \( W_j, RID_j \) and \( W_i \) (the long-term secrets). Without this knowledge, deriving the session key \( SK_{ij} \) is an impossible problem for \( A \). Hence, winning chance of \( G_2 \) has not benefited by eavesdropping. Therefore, we have:

\[
\text{Pr}[\text{SUC}_1] = \text{Pr}[\text{SUC}_2].
\]

**Game3** \((G_3)\): \( G_3 \) models the real and active attack with additional \( \text{Send}(I^*, \text{msg}) \) and \( \text{hsh} \) query simulations. \( A \) intends that a participant may accept the forged message. \( A \) is considered as capable enough to make different \( HO \)
queries for examining the collision existence in hash. However, in login and authentication phase, all the messages \([\overline{T}_1, H_1, U_1, C_s, T_1]\), \(m_2 = \{U_j, H_j, T_2\}\) and \(SK_{ij}\) contain respective participant’s identity, timestamps and random number. Hence, querying \(Send\) oracle do not return collision to \(A\). The results of birthday paradox gives:

\[
Pr[SUC_2] - Pr[SUC_3] \leq \frac{q_{hash}}{2|hash|}. \tag{3}
\]

**Game4** \((G_4)\): \(G_4\) is transformed into \(G_4\), where \(G_4\) is the last game. It is modeled further as an active attack. As illustrated in \(G_2\), To calculate session key \(SK_{ij}\) requires the ephemeral secrets \(y\) and \(z\), and the long-term secrets \(W_i\), \(RID\), and \(W_j\). Having the eavesdropping \(U_i = r_iG\) and \(U_j = r_jG\), adversary requires to differentiate between \(r_i\) and \(r_j\) and a random number, which reduces to the \(ECDDHP\) problem. Hence, it is clear that the computation of \(SK_{ij}\) depends on the \(ECDDHP\) problem. Its’ result follow that

\[
Pr[SUC_3] - Pr[SUC_4] \leq Adv_x^{ECDDHP}(t). \tag{4}
\]

In \(G_4\), all the random oracles are simulated. \(A\) is only left to guess \(\beta\) for winning the game after querying the \(Test\) oracle. Therefore, we have:

\[
Pr[SUC_4] = \frac{1}{2}. \tag{5}
\]

From Equations 1 and 2, we have

\[
\frac{1}{2}Adv^{AKA}_{DRMAS} = |Pr[SUC_1] - \frac{1}{2}| = |Pr[SUC_2] - \frac{1}{2}|. \tag{6}
\]

The triangular inequality and equations 3, 4, 5 give the following:

\[
|Pr[SUC_2] - \frac{1}{2}| = |Pr[SUC_2] - Pr[SUC_4]| \\
\leq |Pr[SUC_2] - Pr[SUC_3]| + |Pr[SUC_3] - Pr[SUC_4]| \\
\leq \frac{q_{hash}}{2|hash|} + Adv^{ECDDHP}_4. \tag{7}
\]

From equations 6 and 7 finally, we have

\[
Adv^{AKA}_p \leq \frac{q_{hash}}{2|hash|} + 2Adv^{ECDDHP}_4. \tag{8}
\]

**V. COMPARATIVE SECURITY AND PERFORMANCE ANALYSIS**

Following subsections present the computation and communication efficiencies comparison of \(DRMAS\) with scheme proposed in [11], [12], [20], [22]–[24].

**A. COMPUTATION COST**

For computation cost analysis, some notations are introduced. \(T_{emp}, T_{epa}, T_h, T_pb, T_{ex}\) and \(T_{en}\) represent ECC point multiplication, addition, hash, bilinear operation, exponentiation and symmetric encryption/decryption operations. For computation cost analysis, the experiment conducted on a PC with DUAL CPU E2200, 2.20 GHz processor, 2048 MB of RAM implemented over Ubuntu OS with PBC Library by Kilinc and Yanik [39] is considered. As per [39], the running time of \(T_{emp} = 5.811\) ms, \(T_{ex} = 3.85\) ms, \(T_{epa} = 2.226\) ms, \(T_{en} = 0.0288\) ms, \(T_{epa} = 0.0046\) ms and \(T_{tk} = 0.0023\). \(DRMAS\) has quasi low computation cost as compared with

\[
DRMAS \approx 20.11\) ms.
\]

**TABLE 2. Computational Cost Analysis.**

| Scheme | Total | Running time |
|--------|-------|--------------|
| [20]   | 42T_{emp} + 2T_{ex} + 7T_{pb} + 3T_{h} | \approx 34.0582 ms |
| [22]   | 2T_{emp} + 20T_{h} | \approx 4.498 ms |
| [23]   | 5T_{emp} + 2T_{ex} + 18T_{h} | \approx 11.1806 ms |
| [11]   | 7T_{emp} + 2T_{ex} + 2T_{pb} + 10T_{h} | \approx 34.9273 ms |
| [12]   | 5T_{emp} + 2T_{ex} + 2T_{pb} + 12T_{h} | \approx 30.4976 ms |
| [24]   | 4T_{emp} + 2T_{pb} + 12T_{h} | \approx 8.9316 ms |

**TABLE 3. Communication Cost Analysis.**

| Scheme     | Messages Exchanged | Bits Exchanged |
|------------|--------------------|----------------|
| Mahmood et al. [20] | 3 | 1340 |
| Challa et al. [22] | 3 | 1536 |
| S. A. Chaudhry et al. [23] | 3 | 2080 |
| Odelu et al. [11] | 3 | 1920 |
| Tsai and Lu [12] | 3 | 1408 |
| Kumar et al. [24] | 3 | 1376 |
| **DRMAS** | 2 | 1344 |

**B. COMMUNICATION COST**

For communication cost comparisons, some common assumptions regarding the sizes of different transmitted parameters are considered as: identity size is fixed at 160 bits, \(SHA - 1\) is selected with 160 bits digest size, 160 bits long random number generation is selected; while the size of timestamp is taken as 32 bits long and the ECC points with 320 bits length are considered to provide same security as of RSA 1024 bits. Proposed \(DRMAS\) completes authentication through transmission of two messages: 1) \(m_1 = \{\overline{T}_1, H_1, U_1, C_s, T_1\}\) from \(SD\) to \(UC\), and \(m_2 = \{U_j, H_j, T_2\}\) from \(UC\) to \(SD\). The length of \(m_1\) is \((160+160+160+320+32) = 832\) bits and the size of \(m_2\) is \((320+160+32) = 512\). Therefore, total communication cost of \(DRMAS\) is 1344 bits, whereas, communication cost of scheme proposed by Kumar et al. [24] is 1376 bits. The communication costs of [11], [12], [20], [22] is 1408, 1920, 1536 respectively; whereas, the communication cost of scheme [23] is 2080 bits. Table 3 shows that \(DRMAS\) has lowest communication cost as compared with competitive scheme. Moreover, proposed \(DRMAS\) completes whole authentication process in just 2 messages, while all other schemes [11], [12], [20], [22]–[24] complete the same in 3 messages.

**C. SECURITY FEATURES**

The security features comparisons of the proposed \(DRMAS\) and competing schemes proposed in [11], [12], [20], [22]–[24] is depicted in Table 4 under the threat model (DY model) solicited in subsection I-B. The Table 4 mentions that only proposed \(DRMAS\) resists known attacks and provides known security features under DY threat model. Due to the
TABLE 4. Security Features.

| Ours       | [24] | [11] | [12] | [20] | [22] | [23] |
|------------|------|------|------|------|------|------|
| S[f_1]     | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    |
| S[f_2]     | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    |
| S[f_3]     | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    |
| S[f_4]     | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    |
| S[f_5]     | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    |
| S[f_6]     | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    |
| S[f_7]     | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    |
| S[f_8]     | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    |
| S[f_9]     | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    |
| S[f_10]    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    |
| S[f_11]    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    |

Note: S[f_1]: Correctness; S[f_2]: Resist Impersonation; S[f_3]: Resist Replay; S[f_4]: D2D Direct Communication; S[f_5]: Resist Privileged Insider; S[f_6]: man in the middle S[f_7]: Session key Security; S[f_8]: Dynamic node addition; S[f_9]: Device anonymity; S[f_10]: Initial Device Verification; S[f_11]: Perfect Forward Secrecy ✓ Secure or extends ✓ Insecure; secure against or not provides

non-verification of initial message from SD_i, UC_j, the scheme proposed by Kumar et al. can become prey of an attacker bombardment of randomly generated illegal messages, which can eventually cause denial of services attack. As proposed in [23], the scheme proposed in [22] suffers from incorrectness and no initial verification issues as of Kumar et al.’s scheme [24], the scheme proposed in [22] also lacks direct device to device (D2D) communication and requires intermediate party, which can become bottleneck for efficiency. Nevertheless, the scheme proposed in [23] also lacks direct D2D communication and scheme proposed in [20] lacks initial verification of request message. The scheme proposed in [12] lacks the procedure to add post-deployment dynamic addition of devices; whereas, citing [12], the scheme proposed in [11] is weak against privileged insider and does not provide anonymity and session key security. The scheme proposed in [11] also lacks the initial request message verification. Therefore, proposed scheme is best suitable for deployment in smart grid environments.

VI. CONCLUSION

In smart grid (SG), the demand response is maintained dynamically through exchanging data between entities. However, this data transfer requires an efficient and secure authentication scheme to avoid any modification over open channel. To secure demand response management, we proposed an authentication scheme (DRMAS) using ECC based certificate. To prove the robustness, DRMAS is analyzed formally along with a discussion on security requirements to confirm formally and informally the robustness of the proposed scheme. DRMAS performs better in communication cost and achieves authentication in just 2 message exchanges. It is also shown that DRMAS provides best tradeoff between security and performance.

REFERENCES

[1] V. C. Gungor, D. Sahin, T. Kocak, S. Ergut, C. Bucella, C. Cecati, and G. P. Hancke, “Smart grid technologies: Communication technologies and standards,” IEEE Trans. Ind. Informat., vol. 7, no. 4, pp. 529–539, Nov. 2011.

[2] A. R. Metke and R. L. Ekl, “Security technology for smart grid networks,” IEEE Trans. Smart Grid, vol. 1, no. 1, pp. 99–107, Jun. 2010.

[3] X. Wang, L. T. Yang, J. Feng, X. Chen, and M. J. Deen, “A tensor-based big service framework for enhanced living environments,” IEEE Cloud Comput., vol. 3, no. 6, pp. 36–43, Nov. 2016.

[4] R. Gupta, S. Tanwar, F. Al-Turjman, P. Italiya, A. Nauman, and S. W. Kim, “Smart contract privacy protection using AI in cyber-physical systems: Tools, techniques and challenges,” IEEE Access, vol. 8, pp. 24746–24772, 2020.

[5] Z. Ali, S. A. Chaudhry, M. S. Ramzan, and F. Al-Turjman, “Securing smart city surveillance: A lightweight authentication mechanism for unmanned vehicles,” IEEE Access, vol. 8, pp. 43711–43724, 2020.

[6] F. Ullah, H. Naeem, S. Jabbar, S. Khalid, M. A. Latif, F. Al-Turjman, and L. Mostarda, “Cyber security threats detection in Internet of Things using deep learning approach,” IEEE Access, vol. 7, pp. 124379–124389, 2019.

[7] S. H. Islam, “A provably secure ID-based mutual authentication and key agreement scheme for mobile multi-server environment without ESSL attack,” Wireless Pers. Commun., vol. 79, no. 3, pp. 1975–1991, Dec. 2014.

[8] A. Ghani, K. Mansoor, S. Mehmood, S. A. Chaudhry, A. U. Rahman, and M. Najmus Saqib, “Security and key management in IoT-based wireless sensor networks: An authentication protocol using symmetric key,” Int. J. Commun. Syst., vol. 32, no. 16, p. e4139, Nov. 2019.

[9] A. Irshad, S. A. Chaudhry, M. Shafiq, M. Usman, M. Asif, and A. Ghani, “A provable and secure mobile user authentication scheme for mobile cloud computing services,” Int. J. Comput. Syst. Sci., vol. 32, no. 14, p. e3980, Sep. 2019.

[10] S. H. Islam and G. P. Biswas, “A more efficient and secure ID-based remote mutual authentication with key agreement scheme for mobile devices on elliptic curve cryptosystem,” J. Syst. Softw., vol. 84, no. 11, pp. 1892–1898, Nov. 2011.

[11] V. Odelu, A. K. Das, M. Wazid, and M. Conti, “Provably secure authenticated key agreement scheme for smart grid,” IEEE Trans. Smart Grid, vol. 9, no. 3, pp. 1900–1910, May 2018.

[12] J.-L. Tsai and N.-W. Lo, “Secure anonymous key distribution scheme for smart grid,” IEEE Trans. Smart Grid, vol. 7, no. 2, pp. 906–914, Mar. 2016.

[13] I. Doh, J. Lim, and K. Chae, “Secure authentication for structured smart grid system,” in Proc. 9th Int. Conf. Innov. Mobile Internet Services Ubiquitous Comput., Fukuoka, Japan, Jul. 2015, pp. 200–204.

[14] N. Saxena, B. J. Choi, and R. Lu, “Authorization and authentication scheme for various user roles and devices in smart grid,” IEEE Trans. Inf. Forensics Secur., vol. 11, no. 5, pp. 907–921, May 2016.

[15] D. He, L. Wang, H. Wang, and M. K. Khan, “Lightweight anonymous key distribution scheme for smart grid using elliptic curve cryptography,” IET Commun., vol. 10, no. 14, pp. 1795–1802, Sep. 2016.

[16] A. Mohammadali, M. S. Haghhighi, M. H. Tadayon, and A. Mohammad-Noodooshan, “A novel identity-based key establishment method for advanced metering infrastructure in smart grid,” IEEE Trans. Smart Grid, vol. 9, no. 4, pp. 2834–2842, Jul. 2018.

[17] K. Mahmood, J. Arshad, S. A. Chaudhry, and S. Kumari, “An enhanced anonymous identity-based key agreement protocol for smart grid advanced metering infrastructure,” Int. J. Commun. Syst., vol. 32, no. 16, p. e4137, 2019.

[18] K. Mahmood, S. A. Chaudhry, H. Naqv, S. Kumari, X. Li, and A. K. Sangaiah, “An elliptic curve cryptography based lightweight authentication scheme for smart grid communication,” Future Gener. Comput. Syst., vol. 81, pp. 557–565, Apr. 2018.

[19] D. Abbasinezhad-Mood and M. Nikooghadam, “Design and hardware implementation of a security-enhanced elliptic curve cryptography based lightweight authentication scheme for smart grid communications,” Future Gener. Comput. Syst., vol. 84, pp. 47–57, Jul. 2018.

[20] K. Mahmood, X. Li, S. A. Chaudhry, H. Naqv, S. Kumari, A. K. Sangaiah, and J. J. P. C. Rodrigues, “Pairing based anonymous and secure key agreement protocol for smart grid edge computing infrastructure,” Future Gener. Comput. Syst., vol. 88, pp. 491–500, Nov. 2018.

[21] X.-C. Liang, T.-Y. Wu, Y.-Q. Lee, C.-M. Chen, and J.-H. Yeh, “Cryptanalysis of a pairing-based anonymous key agreement scheme for smart grid,” in Advances in Intelligent Information Hiding and Multimedia Signal Processing, Cham, Switzerland: Springer, 2020, pp. 125–131.

[22] S. Challa, A. K. Das, P. Gope, N. Kumar, P. Wu, E. Yoon, and A. V. Vasilakos, “Design and analysis of authenticated key agreement scheme in cloud-assisted cyber-physical systems,” Future Gener. Comput. Syst., vol. 108, pp. 1267–1286, Jul. 2018.

[23] S. A. Chaudhry, T. Shon, F. Al-Turjman, and M. H. Alsharif, “Correcting design flaws: An improved and cloud assisted key agreement scheme in cyber physical systems,” Comput. Commun., vol. 153, pp. 527–537, Mar. 2020.
networks. He occasionally writes on issues of higher education in Pakistan.

**HOSSAM ALHAKAMI** received the B.Sc. degree in computer science from King Abdulaziz University, Saudi Arabia, in 2004, the M.Sc. degree in Internet software systems from Birmingham University, Birmingham, U.K., in 2009, and the Ph.D. degree in software engineering from De Montfort University, in 2015. From 2004 to 2007, he worked with Software Development Industry, where he implemented several systems and solutions for a national academic institution. His research interests include algorithms, semantic web, and optimization techniques. He focuses on enhancing real-world matching systems using machine learning and data analytics in a context of supporting decision-making.

**ABDULLAH BAZ** (Senior Member, IEEE) received the B.Sc. degree in electrical and computer engineering from Umman Al-Qura University (UQU), in 2002, the M.Sc. degree in electrical and computer engineering from King Abdulaziz University (KAU), in 2007, and the M.Sc. degree in communication and signal processing and the Ph.D. degree in computer system design from Newcastle University, in 2009 and 2014, respectively. He was the Vice-Dean and then the Dean of the Deanship of Scientific Research with UQU, from 2014 to 2020. He is currently an Assistant Professor with the Computer Engineering Department, the Vice-Dean of DFMSEA, the General Director of the Decision Support Center, and the Consultant of the University Vice Chancellor with UQU. His research interests include VLSI design, EDA/CAD tools, coding and modulation schemes, image and vision computing, computer systems and architecture, and digital signal processing. Since 2015, he has been served as a Review Committee Member of the IEEE International Symposium on Circuits and Systems (ISCAS) and a member of the Technical Committee of the IEEE VLSI Systems and Applications. He served as a Reviewer in a number of journals, including the IEEE INTERNET OF THINGS, the IET Computer Vision, the Artificial Intelligence Review, and the IET Circuits, Devices, and Systems.

**FADI AL-TURJMAN** (Member, IEEE) received the Ph.D. degree in computer science from Queen’s University, Kingston, ON, Canada, in 2011. He is a Full Professor and a Research Center Director at Near East University, Nicosia, Cyprus. He is a leading authority in the areas of smart/intelligent, wireless, and mobile networks’ architectures, protocols, deployments, and performance evaluation. His publication history spans over 250 publications in journals, conferences, patents, books, and book chapters, in addition to numerous keynote and plenary talks at flagship venues. He has authored and edited more than 25 books about cognition, security, and wireless sensor networks’ deployments in smart environments, published by Taylor and Francis, Elsevier, and Springer. He has received several recognitions and best papers’ awards at top international conferences. He also received the prestigious Best Research Paper Award from Computer Communications (Elsevier) journal for the period 2015–2018, in addition to the Top Researcher Award for 2018 at Antalya Bilim University, Turkey. He has led a number of international symposia and workshops in flagship communication society conferences. He currently serves as an Associate Editor and the Lead Guest/Associate Editor for several well reputed journals, including the IEEE COMMUNICATIONS SURVEYS AND TUTORIALS (IF 22.9) and the Sustainable Cities and Society (Elsevier) (IF 4.7).

---

**SHEHZAD ASHRAF CHAUDHRY** received the master’s and Ph.D. degrees (Hons.) from International Islamic University, Islamabad, Pakistan, in 2009 and 2016, respectively. He is currently working as an Associate Professor with the Department of Computer Engineering, Faculty of Engineering and Architecture, Istanbul Gelisim University, Istanbul, Turkey. He has authored over 90 scientific publications appeared in different international journals and proceedings, including more than 68 in SCI/E journals. With an H-index of 23 and an I-10 index 43, his work has been cited over 16,000 times. He has also supervised over 35 graduate students in their research. His current research interests include lightweight cryptography, elliptic/hyper elliptic curve cryptography, multimedia security, E-payment systems, MANETs, SIP authentication, smart grid security, IP multimedia subsystems, and next generation networks.