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Terminal independent security token derivation scheme for ultra-dense IoT networks

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A R T I C L E I N F O

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5G

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A B S T R A C T

The Fifth Generation (5G) networks deploy base station ultra-densification to boost data rates, capacities, reli- ability, energy efficiency as well as the reduction of communication latencies. To increase quality of service as well as quality of experience, a large number of Internet of Things (IoT) communications are relayed over 5G networks. For enhanced pervasive computing, most of the devices in 5G-IoT networks are continuously con- nected to the network, exchanging massive and sensitive data. Therefore, there is need to protect these networks from both privacy and security attacks. As a result, many security protocols have been presented in literature. Unfortunately, IoT devices are heterogeneous in nature with diverse communication and security architectures. These issues render privacy and security protection extremely challenging. Consequently, majority of the con- ventional protocols fail to fully address privacy and security issues in 5G-IoT networks. Particularly, user collusion, de-synchronization and side-channeling attacks are ignored in most of the security protocols. On the other hand, some of the developed protocols achieve salient security but at extremely high computation, storage

and communication complexities. In this paper, an elliptic curve and biometric based security token derivation scheme is presented. Formal security analysis using Burrows–Abadi–Needham (BAN) logic shows the negotiation of a session key between the communicating parties. On the other hand, informal security analysis shows that

this scheme is secure under all the Canetti- Krawczyk (CK) threat model assumptions. In terms of efficiency, the comparative performance evaluation carried out shows that this protocol has the least communication and computation complexities among other related protocols.

# Introduction

The Internet of Things (IoT) comprises of numerous smart devices that are linked together via the internet. The sensors installed in these IoT devices collect data from the environment and transmit the same data to other devices or their operators [[1](#_bookmark22)]. As such, these devices have found applications in a wide range of fields such as in intelligent transportation, military, industrial sector, healthcare, smart grids, vehicular communication, smart homes, environmental monitoring and smart cities [[2](#_bookmark23)]. To enhance Quality of Service (QoS) and satisfy different user requirements, IoT communications are relayed over Fifth Generation (5G) networks. This is due to the extremely low latencies, high energy efficiency, enhanced capacities, reliability, high speeds as well as flexibility of the 5G networks. As such, 5G- IoT based pervasive connectivity overcomes issues such as network resource management and slow response times. As explained in Ref. [[3](#_bookmark24)], 5G-IoT has revolu- tionized healthcare management through remote patient diagnosis, treatment and monitoring.

Although 5G-IoT networks play critical roles in people’s lives, many vulnerabilities lurk in these networks. As such, the collected and

transmitted data is exposed to numerous storage and security threats [[4](#_bookmark25)]. For instance, remote access of medical data over open wireless channels [[5](#_bookmark26)] introduces risks and challenges regarding the preservation of confidentiality, integrity and security [[3](#_bookmark24)]. In military and civilian applications, Internet of Drones (IoD) has been deployed to offer reconnaissance, remote training and remote process monitoring. How- ever, during communication with other drones or control rooms in ground stations, security and privacy have been noted to be serious challenges [[6](#_bookmark27)]. In smart grids, 5G networks have been crucial in the digitization of power grids to offer higher speeds, low latencies and enhanced reliability [[7](#_bookmark28)]. Unfortunately, the deployment of these public 5G networks introduces numerous privacy and security risks to the smart grid infrastructure. As explained in Ref. [[8](#_bookmark29)], majority of the se- curity and privacy issues in 5G-IoT can be attributed to pervasive and continuous connection of the smart devices to the network. As such, these devices are susceptible to Denial of Service (DoS), impersonation,

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packet replays, repudiation, traceability, eavesdropping and Man-in-the-Middle (MitM) attacks.

It is evident that 5G-IoT networks collect massive data that need proper protection. This is critical due to the private and sensitive nature of this data. As explained in Ref. [[9](#_bookmark30)], IoT message exchanges lack pri- vacy and security protection. As such, authentication and device loca- tion identification are crucial in preventing network invasion by malicious devices [[10](#_bookmark31)]. To this end, 5G Authentication and Key Agree- ment protocol (5G AKA) has been deployed to offer identity privacy. In addition, this AKA protocol helps address fake base station attacks which are common in the Fourth Generation (4G) networks. However, trace- ability attacks against IoT devices still remains unresolved [[11](#_bookmark32)] in 5G networks.

* 1. *Research motivation*

The need to improve QoS and security in IoT networks has led to the adoption of 5G networks for message relay among the devices. The high capacities offered by 5G networks has facilitated massive private and sensitive data exchanges among the 5G-IoT devices, which can have devastating effects if compromised by adversaries. In addition, base station ultra-densification in 5G implies frequent handovers and hence frequent authentications to curb attacks. Owing to the resource con- strained nature of IoT devices, conventional security protocols with high computation, communication and storage complexities are unsuitable in this communication environment. Another challenge in 5G-IoT net- works is the device heterogeneity in which communication and security architectures differ from one device to the other. As such, the attainment of high levels of security and privacy protection at optimum levels of QoS is necessary but challenging. As such, there is need for more effi- cient authentication and key exchange protocols.

* 1. *Threat model*

Most of the communication in 5G-IoT is over insecure wireless public channels. As such, the exchanged messages are susceptible to a myriad of privacy and security attacks. In this insecure communication envi- ronment, the attacker capabilities are better modeled using the Canetti- Krawczyk (CK) threat model. Under this model, an adversary Å is assumed to have the following abilities:

* Can eavesdrop the data exchanged in 5G-IoT environment
* Is capable of intercepting and modifying the exchanged data
* Can insert bogus messages into the communication channel
* Has capabilities of deleting some of the transmitted messages
* Can compromise secret security tokens such as private keys, session states information and session keys
* Is able to physically capture the IoT devices and extract stored secrets through power analysis

Under the above assumptions, adversary Å can launch attacks such as impersonation, packet replays, side-channeling, man-in-the-middle, privileged insider and ephemeral secret leakages.

* 1. *Research contributions*

Many privacy and security preservation protocols have been devel- oped, based on technologies such as passwords, smart cards, public key infrastructure and blockchains. However, most of these protocols have serious privacy and security vulnerabilities. In addition, some of these schemes have high complexities which are unsuitable for IoT devices. To this end, the contributions of this paper are as follows:

* A scheme that leverages on elliptic curve cryptography and bio- metrics is developed to directly authenticate the communicating

entities devoid of a central authority. This potentially eliminates single point of failure issues.

* An authorization mechanism is implemented using some security

tokens for access and membership validation, as well as admittance

right groups. This serves to prevent user collusion and privileged insider attacks.

* Formal security analysis is carried out using the widely accepted

BAN logic, which demonstrates the existence of a session key be-

tween the communicating entities. Informal security analysis is also executed to show that this scheme is secure under all the Canetti- Krawczyk (CK) threat model assumptions.

* In terms of efficiency, comparative performance evaluation is carried

out to show that the proposed protocol has the least computation and

communication complexities.

The rest of this paper is organized as follows: Section [2](#_bookmark1) discusses related work, while Section [3](#_bookmark3) describes the system model of the pro- posed scheme. On the other hand, Section [4](#_bookmark9) presents security analysis of the proposed scheme while Section [5](#_bookmark17) presents the comparative perfor- mance evaluation of this protocol. Towards the end of this paper, Sec- tion [6](#_bookmark21) concludes the paper and gives future research directions.

# Related work

Over the recent past, many security and privacy preservation pro- tocols have been presented in literature. For instance, a cross-layer authentication scheme is developed in Ref. [[12](#_bookmark33)] for ultra-dense 5G networks. However, this protocol has scalability issues since it is eval- uated in a very limited scenario. Based on Elliptic Curve Cryptography (ECC) and hash functions, a Device to Device (D2D) authentication scheme is introduced in Ref. [[13](#_bookmark34)]. Unfortunately, this protocol has extensive communication and computation overheads. In addition, it fails to offer untraceability and device anonymity. The three-factor authentication protocol in Ref. [[14](#_bookmark35)] is lightweight and hence can address the issues in Ref. [[13](#_bookmark34)]. However, the scheme in Ref. [[14](#_bookmark35)] cannot provide backward and forward key secrecy. In addition, its design fails to consider collusion, replay and offline password guessing attacks. Similarly, the anonymous multi-server authentication protocol in Ref. [[15](#_bookmark36)] can solve anonymity challenges in Ref. [[13](#_bookmark34)]. Unfortunately, the repeated entry of unique identity during login sessions can poten- tially lead to loss of user untraceability in Ref. [[15](#_bookmark36)]. To offer privacy protection, many blockchain-based schemes have been developed. For example, a chameleon hash functions and blockchain based protocol is introduced in Ref. [[16](#_bookmark37)], while a homomorphic encryption technique based on blockchains is presented in Ref. [[17](#_bookmark38)]. Similarly, a blockchain-based data management scheme is developed in Ref. [[6](#_bookmark27)] for IoD communications, while authentication techniques based on block- chain are presented in Refs. [[18](#_bookmark39),[19](#_bookmark40)] for 5G ultra-dense networks. Moreover, a consortium blockchain based technique is introduced in Ref. [[20](#_bookmark41)], while an authentication scheme using blockchains is devel- oped in Ref. [[10](#_bookmark31)] for smart city 5G-IoT communication. However, blockchain technology can potentially lead to high storage and computation complexities [[21](#_bookmark42)].

To solve performance issues in blockchain-based protocols, the effi- cient and secure scheme in Ref. [[22](#_bookmark43)] can be deployed. Unfortunately, this protocol cannot withstand side channeling attacks and it fails to offer mutual authentication [[6](#_bookmark27)]. To address authentication issues in Ref. [[22](#_bookmark43)], the scheme in Ref. [[23](#_bookmark44)] has been developed. Although this scheme is secure and resists many attacks, it cannot offer forward key secrecy and is still vulnerable to privileged insider attacks. To solve forward key secrecy challenges in Ref. [[23](#_bookmark44)], the ECC and quantum cryptography based scheme in Ref. [[24](#_bookmark45)] can be deployed to encipher information exchanged between devices and 5G base stations. Although this protocol attains non-repudiation, confidentiality, availability and integrity in 5G-IoT environment, its real feasibility and performance evaluation are missing. To offer session key negotiation and access

**Fig. 1.** Network architecture.



control, the protocol in Ref. [[25](#_bookmark46)] is introduced. Although this approach is resilient against replay and impersonation attacks, it cannot offer mutual authentication and protection against side-channeling attacks [[6](#_bookmark27)]. To address mutual authentication challenges in Ref. [[25](#_bookmark46)], the public key based IoT authentication protocol is introduced in Ref. [[26](#_bookmark47)]. How- ever, the deployed Public Key Infrastructure (PKI) results in high computation and communication overheads [[27](#_bookmark48)]. Similarly, the PKI-based scheme in Ref. [[28](#_bookmark49)] has performance issues occasioned by key management challenges.

To address high computation and communication challenges in PKI based protocols, the lightweight ECC based batch authentication pro- tocol in Ref. [[29](#_bookmark50)] and chaotic map based protocols such as the one in Ref. [[30](#_bookmark51)] can be utilized. Unfortunately, the protocol in Ref. [[30](#_bookmark51)] fails to offer user anonymity and cannot withstand privileged insider attacks [[4](#_bookmark25)]. On its part, the protocol in Ref. [[29](#_bookmark50)] deploys trusted authority which presents a potential single point of failure [[31](#_bookmark52)]. Since the protocol in Ref. [[32](#_bookmark53)] is based on simple hash function, it is efficient and can therefore solve performance issues in PKI based schemes. Unfortunately, this scheme cannot provide anonymity and protection against imper- sonation attacks [[33](#_bookmark54)]. To curb these attacks, trusted authority based schemes in Refs. [[34](#_bookmark55),[35](#_bookmark56)] can be utilized. However, these protocols are vulnerable to single point of failure just like the scheme in Ref. [[29](#_bookmark50)]. To protect against message non-repudiation during discovery and trans- mission phases of D2D communication, an identity and ECC based protocol in Ref. [[36](#_bookmark57)] is presented. However, identity based schemes have key escrow issues [[37](#_bookmark58)]. Although the protocol in Ref. [[38](#_bookmark59)] ad- dresses this challenge, it fails to provide device anonymity and protec- tion against privileged insider attacks. In addition, it has extensive

communication and computation overheads [[10](#_bookmark31)]. Side–channeling at- tacks are serious challenges in IoT environments. This is because most of

these devices such as drones are deployed in insecure environments and hence prone to physical captures. As such, Physical Unclonable Func- tions (PUF) based authentication protocols have been introduced. For instance, a PUF-based scheme is introduced in Ref. [[39](#_bookmark60)] for IoT devices. However, this scheme fails to provide user and device anonymity as well as untraceability. In addition, PUF-based schemes have stability issues [[40](#_bookmark61)]. To address these stability issues, authentication protocols in Refs. [[41](#_bookmark62),[42](#_bookmark63)] have been introduced. However, the approach in Ref. [[41](#_bookmark62)] has extensive communication costs. It also fails to consider collusion and de-synchronization attacks in its design. On its part, the protocol in Ref. [[42](#_bookmark63)] cannot protect against user tracking and privileged insider attacks [[43](#_bookmark64)]. Consequently, the authors in Ref. [[43](#_bookmark64)] have developed an anonymous three-factor authentication scheme to address these flaws.

The discussions above clearly show that most of the current IoT se- curity protocols fail to provide some crucial security and privacy fea- tures, while others have very high communication and computation complexities. To address some of these challenges, this paper presents a lightweight authentication, authorization and key agreement scheme based on ECC and biometrics. This protocol is shown to offer mutual authentication, session key agreement, anonymity, untraceability as well as backward and forward key secrecy. In addition, the proposed

scheme is demonstrated to be resilient against majority of the 5G-IoT attacks such as side-channeling, privileged insider, impersonation, de- synchronization, collusion, stolen verifier, MitM, ephemeral secret leakages (ESL), replay, known secret key and offline password guessing. Moreover, this scheme is shown to have the least communication and computation complexities among other related protocols.

# System model

In this section, the mathematical preliminaries, network model as well as the proposed scheme are described.

* 1. *Mathematical preliminaries*

This section presents some mathematical formulations of the cryp- tographic primitives deployed in this paper. These include the elliptic curve discrete logarithmic problem, elliptic curve computational Diffie- Hellman problem, fuzzy extractor probabilistic and deterministic algorithms.

* + 1. *Elliptic curve cryptography*

equation of this elliptic curve is written as *y2* = *x3* + *ax* + *b mod P*, where Suppose that *a* and *b* are points on an elliptic curve *E*. Then, the denoted as *Fq*, where *q* is another large prime number. As such, *a*, *b* ∈ *Fq P* is a large prime number. The finite field over this elliptic curve is

satisfy the condition that *4a3* + *27b2* ∕= 0 mod *q*. Here, the cyclic group of

order *s* is denoted as *Gs* = *P*, where *s* is another prime number. Under these conditions, the following definitions hold:

an adversary needs to find a when provided with point M ∈ Gs. Here, *a* ∈ **Definition 1**. In Elliptic Curve Discrete Logarithmic Problem (ECDLP), *Z*\* and M = aP.

*s*

**Definition 2**. In Elliptic Curve Computational Diffie-Hellman Problem (ECCDHP), an attacker is required to find abP when provided with both

aP and *bP*, where *a*, *b* ∈ *Z*\*.

*s*

* + 1. *Fuzzy extraction*

Suppose that *εi* is an arbitrary string, *β* is the user biometric and *νi* is some auxiliary or helper string. Here, string *εi* can be extracted from biometric template *β* by the fuzzy extractor in an error-free manner. Provided that some other templates of biometric *β\** remain close to *β*, then string *εi* remains constant with the use of helper string *νi*. In essence,

each Fuzzy Extractor (FE) has two probabilistic and deterministic al- gorithms *Rep (.)* and *Gen (.)*. Under this conditions, the following hold:

*Gen (β)* = *(εi, νi):* Given some biometric template *β* as the input to the fuzzy extractor, the probabilistic algorithm *Gen (.)* outputs some

secret biometric key *εi* and auxiliary string *νi.*

**Table 1**

Notations.

Symbol Description

PFF Prime finite field

q Large prime number

DVi, DVj Device i & device j

IDU, PWU User unique identity and password

PVK gNB private key

PUK gNB public key

IDg gNB identity

MVT Membership validation token

AVT Access validation token

ℕi Random number

h(.) Hashing operation

MA Admittance right mask

ΔFE Fuzzy extraction error tolerance limit

IDVi, IDVj Unique identity for DVi & DVj

SKg—Di Shared key between the gNB and DVi

SKg—Dj Shared key between the gNB and DVj

TSi Timestamp i

ℤK Session key

ΔTS Maximum delay tolerance

Γ User temporary identity

|| Concatenation operation

⊕ XOR operation

comprises of elements such as clouds, data centers and servers. As such, any requested service in this 5G-IoT environment is relayed through the gNB. This base station may need to connected to the data centers and servers located in the internet to obtain some of the services and data. The routers and gateways in the core network are critical for these internet connections.

* 1. *The proposed scheme*

The four phases that make up the proposed scheme include the initialization phase; user registration; login, authentication and key negotiation (LAK); and parameter update phase. The specific details of these phases are described in the sub-sections below.

* + 1. *Initialization phase*

All the IoT devices are required to obtain security tokens from the gNB before they could transmit any packets with other devices. To accomplish, the following five steps are executed.

**Step 1:** The gNB selects its identity IDg and elliptic curve *E* whose prime finite is PFF. In addition, it chooses elliptic curve sub-group *SG* whose generator *P* is of order *q.* This is followed by the generation of

gNB’s private key PVK ∈ *Z*\*. Next, it derives its public key as PUK = (P*.*

*q*

Rep (β\*, *νi*) = (*εi*): Provided with a noisy biometric template *β\** and some auxiliary string *νi* as inputs to fuzzy extractor, then the deter-

ministic algorithm *Rep (.)* serves to reproduce the biometric key *εi.*

Basically, the FE serves to extract biometric information from some biometric template as a random string with some error tolerance ΔFE. In addition, the fuzzy extractor outputs some public string as auxiliary

information. With the help of this public string, FE outputs the same random string in the presence of minor change in the input.

* 1. *Network model*

The network architecture in the proposed scheme comprises of IoT devices DVi, the 5G base station gNB, the users and the Mobile Terminals (MTs). [Fig. 1](#_bookmark2) presents the interaction model among all these commu- nicating entities, while [Table 1](#_bookmark4) presents the notations used in this paper. In this network, the users deploy their MTs to access the IoT devices. Here, these devices can be drones, smart TVs, bulbs, cameras, doors, fridges among others.

On the other hand, 5G offers the backbone through which the mes- sages are exchanged among the IoT devices as well as the users. As shown in [Fig. 1](#_bookmark2), the 5G gNB base station connects with the 5G core network, consisting of routers and gateways among other components. On its part, the 5G core network connects to the internet, which

PVK) as shown in [Fig. 2](#_bookmark5).

**Step 2:** The gNB selects some IoT membership validation token MVT, access rights validation token AVT and some collision-resistant one- way hashing function *h(.).* It then publishes parameter set {E, SG, q, P} to all IoT devices.

**Step 3:** Based on some network sanction policies, the gNB generates indices for various IoT admittance right groups (ARGs) as SPG1,

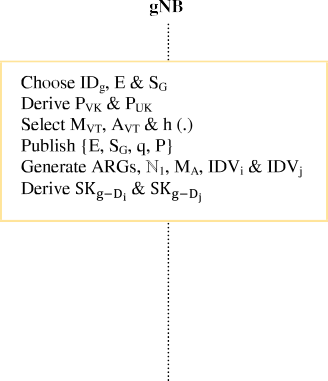
SPGq, ….SPGN, where *N* is the number of ARGs. It then generates random nonce ℕ1 and IoT admittance right mask MA for each IoT

group.

derives key SKg—Di that is shared between the gNB and DVi. Similarly, **Step 4:** The gNB generates unique identity IDVi for DVi. Next, it of key SKg—Dj shared between the gNB and DVj. it generates unique identity IDVj for DVj, followed by the derivation

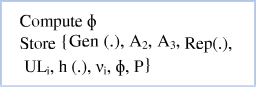
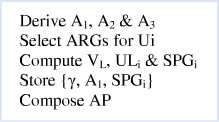
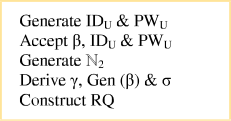
The gNB then securely stores parameter set {IDg, PUK, IDVi, SKg—Di } SKg—Dj } in DVj memory. in DVi memory. Similarly, it securely stores parameter set {IDVi, IDVj,

**Step 5:** The gNB stores parameter set {IDg, PUK, IDVi, SKg—Di , IDVj, SKg—Dj } in its database. Finally, IoT DVi and DVj are deployed in the area of interest.



**Fig. 2.** Initialization phase.

Gen (β) = (εi, νi) and security parameter σ = h (PWU||εi). Lastly it transmits registration request RQ = {γ, σ} to the gNB as shown in [Fig. 3](#_bookmark6).



derives parameters A1 = h (γ||IDg||MVT), A2 = h (γ||σ)⊕A1 and A3 = **Step 2:** Upon receiving message RQ from the user’s MT, the gNB This is basically the qth and (q + k)th rights for the user. h (σ||A1). The gNB then chooses some ARGs suitable for this user.

SPGq as VL = h (A1||AVT||ℕ1), as well as user authorization list ULi = Afterwards, it uses its AVT to derive association value between γ and

{(SPGq, VL), (SPGq + k, BL+2)}. It then transmits associative parameters

AP = {A2, h (.), A3, ULi, P, PUK} to the user over some private channels. Lastly, the gNB derives SPGi = {SPGq, SPGq + k, …} and stores parameter set {γ, A1, SPGi} in its database.

**Fig. 3.** User registration phase.

* + 1. *User Registration Phase*

This phase commences by having the user *Ui* transmit registration request to the gNB over some private channels. This is a three-step process as elaborated below.

**Step 1:** The user generates unique identity IDU and password PWU. Next, user biometric data β, IDU and PWU are input to the user’s

nonce ℕ2 and the derivation of temporary identity γ = h (IDU||ℕ2), mobile terminal MT. This is followed by the generation of random

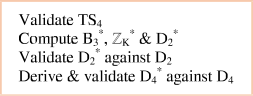
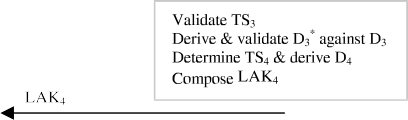
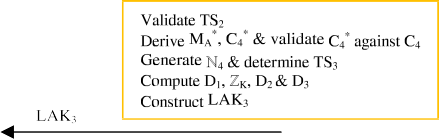
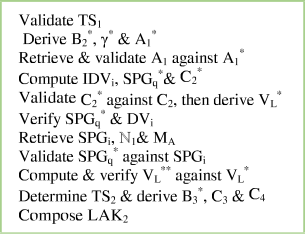
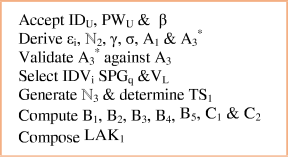
parameter ɸ = ℕ2⊕h(IDU||εi). Finally, the MT store parameter set **Step 3:** After getting AP from the gNB, the user’s MT derives

{Gen (.), A2, A3, Rep (.), ULi, h (.), νi, ɸ, P} in its memory.

* + 1. *Login, authentication and key negotiation phase*

This phase is triggered whenever the user wants some access to the IoT devices, for instance to obtain the collected data. To accomplish this, the following seven steps are executed among the MT, gNB and the IoT devices. After successful mutual authentication, the MT and the IoT devices negotiate a session key for secure packet exchanges. Thereafter, the user can access real-time IoT sensed data that correspond to user access rights.

**Step 1:** Suppose that the user is interested in accessing real-time data in DVi. To accomplish this, the user inputs IDU, PWU and β to the MT



**Fig. 4.** Login, Authentication and Key negotiation Phase.

which then utilizes stored parameters to derive εi = Rep (β, νi), ℕ2 = ɸ⊕h(IDU||εi), γ = h (IDU||ℕ2), σ = h (PWU||εi), A1 = A2⊕ h (γ||σ) and A3\* = h (A1⊕h(γ||PWU||εi)). Next, it checks whether A3\* ≟ A3 such that the login request is rejected if the two do not match. Otherwise,

the MT chooses IDVi and retrieves the corresponding SPGq and VL from the stored ULi.

**Step 2:** The MT generates random nonce ℕ3 ∈ *Z*\* and determines current timestamp TS1 that it uses to compute parameters B1 = ℕ3P, B2 = ℕ3PUK, B3 = γ⊕h (B1||B2), B4 = IDVi⊕h(B2||TS1), B5 = SPGq⊕h

*q*

(A1||TS1), C1 = VL⊕h(γ||TS1) and C2 = h(γ||IDVi||SPGq||A1||B1||B2||

TS1). Finally the MT constructs login request LAK1 = {B1, B3, B4, B5, C1, C2, TS1} that it transmits to the gNB over pubic channels as shown

in [Fig. 4](#_bookmark7).

**Step 3:** After obtaining LAK1 from the MT, the gNB validates TS1

freshness checks, the gNB derives parameters B2\* = B1PVK, γ\* = against the delay tolerance value ΔTS. Provided that LAK1 passes the B3⊕h (B1||B2\*) and A1\* = h (γ\*||IDg||MVT). Next, it uses γ\* to

retrieve the user’s membership A1 from its database. This is followed

by the confirmation of whether this user is a member of this partic- ular gNB. This is achieved by confirming whether A1\* ≟ A1. Provided that these two values are not identical, the gNB rejects the user’s

login request. Otherwise, the gNB computes IDVi = B4⊕h(B2\*||TS1), SPGq\* = B5⊕h(A1\*||TS1) and C2\* = h(γ\*||IDVi||SPGq\*||A1\*||B1|| B2||TS1).

these two values differ. Otherwise, the gNB derives parameter VL\* = It then checks if C2\* ≟ C2 such that the login request is rejected when C1⊕h(γ\*||TS1).

**Step 4:** The gNB confirms whether SPGq\* submitted by the user matches the data access rights of IoT devices DVi. If this is the case, the gNB retrieves SPGi, random nonce ℕ1 and MA for this particular

case, it computes VL\*\* = h (A1\*||AVT||ℕ1). To confirm that this SPGq\*. Next, it validates that this SPGq\* belongs to SPGi. If this is the particular user has rights of SPGq\*, the gNB checks if VL\*\* ≟ VL\*.

Provided that this is not the case, the gNB knows that this user is not permitted to access IoT DVi. As such, it sends access reject response

TS2 and derives B3\* = h (γ\*||IDVi\*||B2\*), C3 = MA⊕h(IDVi\*|| to this user. Otherwise, the gNB determines the current timestamp

SKg—D ⃒⃒ TS2) and C4 = h (B3\*||IDVi\*||MA||B1|| SKg—D ||TS2). Finally,

**Step 6:** On receiving message LAK3 from the DVi, the gNB validates the freshness of timestamp TS3 using delay tolerance threshold ΔTS. Basically, the session is terminated if LAK3 fails the freshness checks.

Otherwise, the gNB computes D3\* = h (B3\*||IDVi||D1||D2|| SKg—Di ⃒⃒

TS3) and confirms whether D3\* ≟ D3. Here, the session is terminated

the current timestamp TS4 and derives D4 = h(γ\*||IDVi||A1\*||D1|| D2||B2\*||TS4). Finally, it constructs authentication message LAK4 = when these two values are dissimilar. Otherwise, the gNB determines

{D1, D3, D4, TS4} that is then transmitted over to the user’s MT.

**Step 7:** After receiving message LAK4 from the gNB, the MT validates timestamp TS4 such that the session is terminated if this check fails.

Otherwise, the MT derives B3\* = h (γ||IDVi||B2), session key ℤK\* = h (B3\*||ℕ3D1) and D2\* = h (IDg||IDVi||ℤK). It then checks if D2\* ≟ D2 such that the session is terminated whenever these values are dis-

the legitimate DVi. Afterwards, the MT derives D4\* = h(γ||IDVi|| similar. Otherwise, the user trusts that this session key is shared with A1\*||D1||D2||B2||TS4) and checks if D4\* ≟ D4. Basically, the session is

terminated when these two parameters are unequal. Otherwise, the gNB, and DVi are authenticated by the user through the MT and share

a session key ℤK with DVi. Similar login, authentication and key negotiation procedures are followed for DVj or any other IoT device

that the user may wish to establish a communication session with.

* + 1. *Parameter update phase*

This phase is triggered whenever the user wants to update password or biometric data. This may be occasioned by the suspicion that these parameters have been compromised by an adversary. To reduce communication overheads, this update is executed locally devoid of gNB involvement. It may also be important that admission rights accorded to the user be changed when there are changes in policies. This change of admission rights is executed between the user and the gNB over some private channels. This is a five-step process as described below.

**Step 1:** The user inputs identity IDU as well as old password PWU. Next, biometric data β is imprinted on the MT after which it derives

εi = Rep (β, νi), ℕ2 = ɸ⊕h(IDU||εi), γ = h (IDU||ℕ2), σ = h (PWU||εi), A1 = A2⊕ h (γ||σ) and A3\* = h (σ||A1).

**Step 2:** The MT checks if A3\* ≟ A3 such that the update is terminated.

This is because it implies that at least one of the authentication pa- rameters is invalid. Otherwise, the MT prompts the user to input new

i i password and biometrics PWNew and βNew respectively. Afterwards,

it composes authentication message LAK2 = {B3\*, C3, B1, C4, TS2}

U

New

it derives Gen (β

) = (εNew, νNew), ɸNew = ℕ ⊕h(ID ||εNew), σNew

that it transmits over to DVi.

New

New

i i

New

New

2 U

New

i

New

**Step 5:** On receiving message LAK2 from the gNB, DVi checks the freshness of timestamp TS2 using ΔTS and terminates the request if

LAK2 fails the freshness checks. Otherwise, DVi derives MA\* = C3⊕h (IDVi\*|| SKg—Di ⃒⃒ TS2) and C4\* = h (B3\*||IDVi\*||MA||B1|| SKg—Di ||

TS2). This is followed by the confirmation of whether C4\* ≟ C4. Here,

the session is terminated if these values are not equivalent. Other-

stamp TS3. Next, it computes D1 = ℕ4P, session key ℤK = h (B3\*|| ℕ3D1), D2 = h (IDg||IDVi||ℤK) and D3 = h (B3\*||IDVi||D1||D2|| wise, DVi generates random nonce ℕ4 and determine current time- SKg—Di ⃒⃒ TS3). Lastly, it composes authentication message LAK3 =

{ℕ4, D2, D3, TS3} that it forwards to the gNB.

**Table 2**

BAN Logic notations.

Notation Meaning

#(G) G is fresh

K⊲ G K sees G

〈G〉R G is combined with secret R

K|≡ G K believes in statement G

K| ~ G K once said statement G

K ↔ *R* S *K* and *S* share secret key *R* for communication with each other

*K*|⇒ G *K* has jurisdiction over formula *G*

= h (PWU ||εi ), A2 = A1⊕h (γ||σ ) and A3 = h (σ ||A1).

Next, the MT substitutes parameter set {A2, A3, νi, ɸ} with its updated

equivalent {ANew, ANew, νNew, ɸNew}.

2 3 i

**Step 3:** To execute admission rights change, the gNB transmits an

update request UR together with γ and new admission right list ULi\* to the MT. This request basically prompts the user that the current

admission rights need to be refreshed.

**Step 4:** After getting request UR from the gNB, the user inputs IDU, PWU and β to the MT. using the stored values in its memory, the MT validates this login attempt as described in the login, authentication

and key negotiation phase. Thereafter, it substitutes stored ULi with ULi\* before sending a response message together with parameter A1 to the gNB. Basically, this message serves to inform the gNB that this update is complete.

**Step 5:** Upon receiving this message, the gNB validates the received user parameter A1. Here, the gNB substitutes the stored SPGi with refreshed the refreshed version SPGNew. Finally, the current admit- tance right groups ARGs is also replaced with its refreshed one ARGsNew for this particular user.

i

# Security analysis

In this section, formal security analysis is executed to show the

**Table 3**

BAN Logic rules.

Rule Description

Using the idealized messages, initial assumptions and the BAN logic rules, the attainment of the four security goals is proved as follows.

Based on LAK1, BAN logic proof 1(BLP1) is obtained:

K| ≡ S⇒G, K| ≡ S| ≡ G

JR: Jurisdiction rule

**BLP :** gNB ⊲ 〈*γ*, IDV , SPG , V , B , TS , MT ↔ *B*2 gNB〉

K| ≡ G

K| ≡ K ↔ RS, K⊲〈G〉R

**1**

MMR: Message meaning rule

i q L 1 1 A1

K ≡ S| ∼ G K| ≡ *#*(G)

K| ≡ *#*(G, H)

FPR: Fresh promotion rule

Using IA6 and MMR on BLP1, BLP2 is obtained:

**BLP :** gNB |≡ DV |~ 〈*γ*, IDV , SPG , V , B , TS , MT ↔ *B*2 gNB〉

K| ≡ *#*(G), K| ≡ S| ∼ G K| ≡ S| ≡ G

NVR: Nonce verification rule

**2** i i

q L 1 1

**Table 4**

Initial assumptions.

Assumption Descriptions

IA1 gNB |≡# (TS1)

IA2 DVi |≡# (TS2)

IA3 gNB |≡# (TS3)

IA4 MT |≡# (TS4)

IA5 MT |≡ (MT ↔ *A*1 gNB)

IA6 gNB |≡ (MT ↔ *A*1 gNB)

Based on IA1 and the FPR.

**BLP3:** gNB |≡# 〈*γ*, IDVi, SPGq, VL, B1, TS1, MT ↔ *B*2 gNB〉

Using NVR on BLP2 and BLP3, BLP4 is yielded:

**BLP4:** gNB |≡ MT|≡ 〈*γ*, IDVi, SPGq, VL, B1, TS1, MT ↔ *B*2 gNB〉

However, based on LAK2, BLP5 is attained:

**BLP :** DV ⊲ 〈IDV , B∗ , M , B , TS 〉

IA7 DV |≡ (DV ↔ *SKg*—*Di* gNB)

**5** i i 3 A 1

2 SKg—Di

i i

**Table 5**

IA8 gNB |≡ (DVi ↔ *SKg*—*Di* gNB)

IA9 MT |≡ DVi|≡ (MT ↔ Z*K* DVi)

IA10 DVi |≡ MT|≡ (MT ↔ Z*K* DVi)

Applying MMR on IA7, BLP6 is obtained as follows.

**BLP6:** DVi |≡ gNB |~ 〈IDVi, B∗ , MA, B1, TS2〉

3

On the other hand, the application of FPR on IA2 results in BLP7:

Idealized messages.

Message Idealized format

**BLP7:** DVi |≡# 〈IDVi, B∗ , MA, B1, TS2〉

MT → gNB

LAK1 = {B1, B3, B4, B5, C1, C2, TS1} gNB → DV1

LAK {B \*, C , B , C , TS }

〈*γ*, IDVi, SPGq, VL, B1, TS1, MT ↔ *B*2 gNB〉A

〈IDVi, B∗ , MA, B1, TS2〉SK

3

1

3 g—Di

Using NVR on BLP6 and BLP7, we obtain.

**BLP :** DV |≡ gNB|≡ 〈IDV , B∗ , M , B , TS 〉

2 = 3 3 1 4 2

DV1 → gNB

LAK3 = {ℕ4, D2, D3, TS3}

gNB → MT

LAK4 = {D1, D3, D4, TS4}

〈IDVi, B∗ , D1, D2, TS3〉SK

〈*γ*, IDVi, D1 , D2 , TS4 〉A1

3

g—Di

**8** i i 3 A 1 2

Based on LAK3, BLP9 is obtained as follows:

**BLP9:** gNB ⊲ 〈IDVi, B∗ , D1, D2, TS3〉SK

3 g—Di

correctness of the proposed scheme. In addition, informal analysis is carried out to show the resilience of the proposed protocol against conventional 5G-IoT attack vectors.

* 1. *Formal security analysis*

The widely adopted Burrows–Abadi–Needham (BAN) logic is deployed to prove the existence of a session key between the user and

DVi. To achieve this, the notations in [Table 2](#_bookmark8) below are utilized:

Next, the four BAN logic rules in [Table 3](#_bookmark10) are also deployed during this formal proof. In essence, JR implies that if *K* trusts that *S* has control over *G* and *K* trusts that *S* trusts *G*, then *K* also trusts *G*. On the other hand, the MMR implies that if *K* trusts that *R* is shared with *S* and *K* sees *G* combined with *R*, then *K* trusts that *S* said *G*.

In addition, the FPR implies that if *K* trusts that *G* is fresh, then *K* trusts that (G, H) is fresh. Similarly, the implication of NVR is that if *K* trusts that *G* is fresh and *K* believes that *S* said *G*, then *K* trusts that *S* trusts *G*. In addition to these BAN logic rules, the ten Initial Assumptions (IAs) in [Table 4](#_bookmark11) are defined.

For effective proofs, all the exchanged messages are transformed into idealized format as shown in [Table 5](#_bookmark12).

Lastly, four security goals (GLs) are formulated as follows:

**G1:** MT |≡ DVi |≡ (MT ↔ Z*K* DVi)

**G2:** MT |≡ (MT ↔ Z*K* DVi)

**G3:** DVi |≡ MT |≡ (MT ↔ Z*K* DVi)

**G4:** DVi |≡ (MT ↔ Z*K* DVi)

Using MMR on IA8, BLP10 is yielded:

**BLP10:** gNB |≡|~ 〈IDVi, B∗ , D1, D2, TS3〉

3

According to IA3 and FPR, the following is attained:

**BLP11:** gNB |≡# 〈IDVi, B∗ , D1, D2, TS3〉

3

To obtain BLP12, NVR is applied to BLP10 and BLP11:

**BLP12:** gNB |≡ DVi |≡ 〈IDVi, B∗ , D1, D2, TS3〉

3

Based on LAK4, the following is obtained:

**BLP13:** MT ⊲ 〈*γ*, IDVi, D1, D2, TS4〉A1

On the other hand, to obtain BLP14, MMR is applied on IA5:

**BLP14:** MT |≡gNB |~ 〈*γ*, IDVi, D1, D2, TS4〉

On the other hand, the application of FPR on IA4 results in BLP15:

**BLP15:** MT |≡# 〈*γ*, IDVi, D1, D2, TS4〉

Using NVR on both BLP14 and BLP15 yields the following.

**BLP16:** MT |≡ gNB |≡ 〈*γ*, IDVi, D1, D2, TS4〉

Since ℤK = h (B3\*||ℕ3D1) and amalgamating BLP12 and BLP16, BLP17 is obtained:

**BLP17:** MT |≡ DVi |≡ (MT ↔ Z*K* DVi), hence **G1** is attained.

On the other hand, the combination of BLP4, BLP8 and the session

key results in BLP18:

**BLP18:** DVi |≡ MT |≡ (MT ↔ Z*K* DVi) and as such, **G3** is achieved. Applying JR on both BLP17 and IA9, BLP19 is obtained:

**BLP19:** MT |≡ (MT ↔ Z*K* DVi), which basically means that **G2** is realized.

Finally, based on JR, IA10 and BLP18, the following is obtained:

**BLP20:** DVi |≡ (MT ↔ Z*K* DVi), which essentially achieves **G4.**

Since the above BAN logic proofs have successfully attained all the

four formulated security goals, it is evident that the proposed protocol realizes mutual authentication as well as session key negotiation be-

tween the user’s MT and DV1. The same procedures can be followed to demonstrate the existence of strong mutual authentication and key

agreement between the user’s MT and any other IoT DVj.

* 1. *Informal security analysis*

In this section, various lemmas are formulated and proofed to show that the proposed scheme is robust against many attack vectors under all the assumptions in the Canetti- Krawczyk (CK) threat model. These as- sumptions are well articulated in Section [1.2](#_bookmark0) above.

**Lemma 1**. *Privileged insider and MiTM attacks are prevented in this*

*IDVi||D*1*||D*2*||* SKg—Di ⃒⃒ *TS*3). *Further*, *it is transmitted as D*3 *and D*4 *in message LAK*4, *where D*4 = h(*γ\*||IDVi||A*1*\*||D*1*||D*2*||B*2*\*||TS*4).

**Lemma 3**. *The communicating parties execute strong mutual authentication*

**Proof**. *In this scheme*, *the gNB and the user authenticate each other through the validation of membership A*1 *as well as parameters C*2 *and D*4. *Here*, *it is*

*membership that can derive parameter C*2, *where C*2 = h(*γ||IDVi||SPGq|| only the user with valid biometrics data β*, *password PWU and gNB issued A*1*||B*1*||B*2*||TS*1). *To authenticate the user*, *the gNB checks whether C*2*\** ≟

*its private key PVK to derive security token B*2*\** = *B*1*PVK*. *Thereafter*, *it C*2. *Upon receiving B*3 *in login request LAK*1 *from the user’s MT*, *the gNB uses computes γ\** = *B*3⊕*h* (*B*1*||B*2*\**) *that it utilizes to compute parameter D*4 = h

*termines whether D*2*\** ≟ *D*2 *and D*4*\** ≟ *D*4, *where D*2*\** = *h* (*IDg||IDVi||*ℤ*K*) (*γ\*||IDVi||A*1*\*||D*1*||D*2*||B*2*\*||TS*4). *To authenticate the gNB*, *the user de- and D*4*\** = *h*(*γ||IDVi||A*1*\*||D*1*||D*2*||B*2*||TS*4). *Similarly*, *DVi authenticates*

*the gNB by checking if C*4*\** ≟ *C*4, *while the gNB authenticates DVi by con-*

*authenticated*. *Devoid of* SKg—Di *and* ℤ*K*, *an adversary is unable to derive firming whether D*3*\** ≟ *D*3. *As such*, *all the three entities are mutually parameters C*4 *and D*2 *respectively*, *and hence its authentication will fail*.

**Lemma 4**. *Collusion attacks are prevented in this scheme*

*during the registration phase*, *where ULi* = {(*SPGq*, *VL*), (*SPGq*+*k*, *BL*+2)}. **Proof**. *To grant the user some access rights*, *the gNB issues the MT with ULi During the login*, *authentication and key negotiation phase*, *the MT uses*

*where LAK*1 = {*B*1, *B*3, *B*4, *B*5, *C*1, *C*2, *TS*1}, *B*5 = *SPGq*⊕*h*(*A*1*||TS*1) *and A*1 *message LAK*1 *to transmit SPGq in parameter B*5 *which is encapsulated in A*1,

= h (*γ||IDg||MVT*). *Similarly*, *VL is sent in C*1 *which is part of message LAK*1,

*where C*1 = *VL*⊕*h*(*γ||TS*1), *VL* = *h* (*A*1*||AVT||ℕ*1) *and γ* = *h* (*IDU||ℕ*2).

*Evidently*, *VL is protected through its encapsulation with γ*. *During the*

*authentication process*, *the gNB verifies that the user has rights of access SPGq\* through checking this value in its database as shown in Step* 4. *Next*, *it*

*confirm that the user has rights of SPGq\* by checking if VL\*\** ≟ *VL\**. *Suppose that an adversary has obtained parameters γ*, *A*1, *and SPGq from some ma-*

*licious user*. *The goal here is for the user to assist the adversary escalate his network access rights*. *However*, *for this collusion attack to succeed*, *the ad-*

*versary needs to derive VAdv* = *h* (*A ||A ||ℕ* ). *Since it is only the gNB that*

*scheme*

*L* 1 *VT* 1

*Adv*

*knows nonce ℕ*1 *and access rights validation token AVT*, *the derived VL will*

*sages LAK*1, *LAK*2, *LAK*3 *and LAK*4 *are exchanged*. *Here*, *LAK*1 = {*B*1, *B*3, *B*4, *B*5, *C*1, *C*2, *TS*1}, *LAK*2 = {*B*3*\**, *C*3, *B*1, *C*4, *TS*2}, *LAK*3 = {*ℕ*4, *D*2, *D*3, **Proof**. *During the login*, *authentication and key negotiation phase*, *mes- TS*3}, *LAK*4 = {*D*1, *D*3, *D*4, *TS*4}, *B*1 = ℕ3*P*, *B*3 = γ⊕h (*B*1*||B*2), *B*4 =

*IDVi*⊕*h* (*B*2*||TS*1), *B*5 = *SPGq*⊕*h*(*A*1*||TS*1), *C*1 = *VL*⊕*h*(*γ||TS*1), *C*2 = h(*γ||*

*IDVi||SPGq||A*1*||B*1*||B*2*||TS*1), *B*3*\** = *h* (*γ\*||IDVi\*||B*2*\**), *C*3 = MA⊕h

(*IDVi\*||* SKg—D ⃒⃒ *TS*2), *C*4 = h (*B*3*\*||IDVi\*||MA||B*1*||* SKg—D *||TS*2), *D*1 =

*be invalid*. *In addition*, *the derivation of parameter A*1 *requires knowledge of user temporary identity γ*, *the gNB unique identity IDg and membership validation token MVT*. *Without all these security parameters*, *the users cannot collude with adversaries to escalate their access rights*.

**Lemma 5**. *This scheme can withstand ephemeral secret leakages and stolen verifier attacks*

i i ⃒⃒

ℕ4*P*, *D*2 = h (*IDg||IDVi||*ℤ*K*), *D*3 = h (*B*3*\*||IDVi||D*1*||D*2*||* SKg—Di ⃒⃒ *TS*3) *and D*4 = h(*γ\*||IDVi||A*1*\*||D*1*||D*2*||B*2*\*||TS*4). *Evidently*, *none of these messages transfers the user password PWU across the network*. *Although*

*parameters γ* = *h* (*IDU||ℕ*2) *and σ* = *h* (*PWU||εi*) *contain identity IDU and password PWU*, *they are masked in random nonce ℕ*2 *and biometric key εi*.

*As such*, *only the user knows IDU and PWU and therefore this scheme with- stands MitM and privileged insider attacks*.

**Lemma 2**. *De-synchronization and traceability attacks are thwarted in the proposed scheme*

**Proof**. *The goal of this attack is to compromise synchronization parameters among the gNB*, *users and IoT devices such that it becomes difficult for the user to login and authenticate*. *To curb this attack*, *the proposed scheme does*

*not require any update of the transient user identity γ*, *where γ* = *h* (*IDU||ℕ*2).

*Although this may inadvertently result in traceability attacks against the user*,

*γ is protected by collision-resistant one-way hashing function*. *In addition*, *it is masked in high entropy random nonce ℕ*2. *Moreover*, *it is encapsulated in parameter B*3 *that is sent as a different value for different messages*. *For*

*instance*, *in message LAK*1, *it is sent as B*3, *where B*3 = γ⊕h (*B*1*||B*2). *However*, *in message LAK*2, *it is sent as B*3*\**, *where B*3*\** = *h* (*γ\*||IDVi\*||B*2*\**). *Similarly*, *in message LAK*3, *it is transmitted as D*3, *where D*3 = h (*B*3*\*||*

**Proof**. *The goal of adversaries in this attack is to steal or modify verifi-*

*To curb this*, *the user only transmits parameter σ* = *h* (*PWU||εi*) *which is cation tokens such as passwords and biometric data from the gNB’s database*. *SPGi*}, *where γ* = *h* (*IDU||ℕ*2) *and A*1 = h (*γ||IDg||MVT*). *Clearly*, *none of the clearly masked in εi*. *In addition*, *the gNB stores only parameter set* {*γ*, *A*1, *stored parameters is associated with user password PWU or biometric data β*.

*Therefore*, *this scheme is robust against ephemeral secret leakages* (*ESL*) *and stolen verifier attacks*.

**Lemma 6**. *The proposed scheme upholds user and device anonymity*

*where RQ* = {*γ*, *σ*} *and AP* = {*A*2, *h* (.), *A*3, *ULi*, *P*, *PUK*}. *Similarly*, *messages* **Proof**. *During the registration phase*, *messages RQ and AP are exchanged*, *and key negotiation phase*. *Here*, *LAK*1 = {*B*1, *B*3, *B*4, *B*5, *C*1, *C*2, *TS*1}, *LAK*2 *LAK*1, *LAK*2, *LAK*3 *and LAK*4 *are exchanged during the login*, *authentication*

= {*B*3*\**, *C*3, *B*1, *C*4, *TS*2}, *LAK*3 = {*ℕ*4, *D*2, *D*3, *TS*3} *and LAK*4 = {*D*1, *D*3,

*D*4, *TS*4}. *Clearly*, *the user’s real identity IDU is never transmitted in these two*

*phases*. *Consequently*, *IDU can never be directly obtained by the eavesdrop- ping of all the exchanged messages*. *Regarding DVi’s identity IDVi*, *its trans-*

*mission is masked in C*2 = h (*γ||IDVi||SPGq||A*1*||B*1*||B*2*||TS*1), *which is part of message LAK*1. *Obviously*, *it is only the gNB that can derive B*2*\** = *B*1*PVK*, *γ\** = *B*3⊕*h* (*B*1*||B*2*\**), *A*1*\** = *h* (*γ\*||IDg||MVT*) *and IDVi\** = *B*4⊕*h* (*B*2*\*||*

*TS*1).

**Lemma 7**. *The proposed scheme upholds user untraceability*

**Proof**. *In this scheme*, *the user temporary identity γ* = *h* (*IDU||ℕ*2) *is deployed in all exchanged messages instead of real identity IDU*. *It is evident*

*that IDU is masked with random nonce ℕ*2 *and collision-resistant one-way hashing function*. *In login request LAK*1, *γ is protected in security parameters*

*B*3, *C*1 = *VL*⊕*h*(*γ||TS*1) *and C*2 = h(*γ||IDVi||SPGq||A*1*||B*1*||B*2*||TS*1). *To obtain IDU from γ*, *the adversary needs to compute ℕ*2 = ɸ⊕h(*IDU||εi*) *and also reverse the one-way hashing function*. *Here*, *εi* = *Rep* (*β*, *νi*) *and hence user biometrics is required to derive ℕ*2. *Since it is computationally infeasible*

*to reverse h(.) and guess biometrics β*, *an adversary can never recover ℕ*2. *As such*, *the attacker can never associate two communication sessions to the same user*. *Suppose that an adversary has captured the derived session keys*

ℤ*K* = *h* (*B*3*\*||ℕ*3*D*1) *and* ℤ*K\** = *h* (*B*3*\*||ℕ*3*D*1). *Next*, *an attempt is made to associate these session keys to some user*. *Here*, *B*3*\** = *h* (*γ\*||IDVi\*||B*2*\**), *γ\**

= *B*3⊕*h* (*B*1*||B*2*\**), *B*2*\** = *B*1*PVK*, *B*1 = ℕ3*P*, *B*2 = ℕ3*PUK*, *B*3 = γ⊕h (*B*1*||B*2)

*and D*1 = ℕ4*P*. *Clearly*, *random nonces ℕ*3 *and ℕ*4 *are incorporated in these session keys*, *which are only known to the MT and DVi respectively*. *Conse-*

*quently*, *these session keys are different for each session and can never be associated with a certain user*.

**Lemma 8**. *The proposed protocol can withstand side-channeling and impersonation attacks*

**Proof**. *The assumption made in these attacks is that the adversary wants to masquerade as a legitimate user*. *To accomplish this*, *side-channeling attack is executed and hence all the security tokens* {*Gen* (.), *A*2, *A*3, *Rep* (.), *ULi*, *h* (.),

*νi*, *ɸ*, *P*} *stored in the MT are extracted*. *In addition*, *all the exchanged*

*messages* {*LAK*1, *LAK*2, *LAK*3, *LAK*4} *in the previous session are captured*.

Case 1: *Suppose that an adversary attempts to derive login request LAK*1

= {*B*1, *B*3, *B*4, *B*5, *C*1, *C*2, *TS*1}. *Here*, *B*1 = ℕ3*P*, *B*2 = ℕ3*PUK*, *B*3 = γ⊕h (*B*1*||B*2), *B*4 = *IDVi*⊕*h*(*B*2*||TS*1), *B*5 = *SPGq*⊕*h*(*A*1*||TS*1), *C*1 = *VL*⊕*h*

(*γ||TS*1), *γ* = *h* (*IDU||ℕ*2), *A*1 = A2⊕ *h* (*γ||σ*), *A*2 = h (*γ||σ*)⊕*A*1, *C*2 = h

(*γ||IDVi||SPGq||A*1*||B*1*||B*2*||TS*1) *and σ* = *h* (*PWU||εi*). *Clearly*, *devoid of valid IDU*, *IDg*, *PWU*, *PUK*, *εi*, *A*1, *ℕ*2 *and ℕ*3, *the construction of any*

*valid LAK*1 *flops*. *It is evident that the captured messages as well as the MT’s memory resident parameters cannot provide the adversary with all the constituents of the login request LAK*1 *and therefore user imperson- ation fails*.

Case 2: *Suppose that the adversary has captured previous session mes- sages and wants to impersonate the gNB so as to fool either the user or IoT device DVi*. *To achieve this*, *attempts are made to construct messages*

*LAK*2 *and LAK*4. *Here*, *LAK*2 = {*B*3*\**, *C*3, *B*1, *C*4, *TS*2}, *LAK*4 = {*D*1, *D*3,

*D* , *TS* }, *B* = ℕ *P*, *B \** = *h* (*γ||IDV ||B* ), *C* = M ⊕h(*IDV \*||* SK ⃒⃒

*in security parameters D*2 *and D*3, *where D*2 = h (*IDg||IDVi||*ℤ*K*) *and D*3 = h (*B*3*\*||IDVi||D*1*||D*2*||* SKg—Di ⃒⃒ *TS*3). *Finally*, *it sends message LAK*3 = {*ℕ*4, *D*2, *D*3, *TS*3} *to the gNB*. *Here*, *parameter D*3*\* is computed as D*3*\** = *h* (*B*3*\*|| IDVi||D*1*||D*2*||* SKg—Di ⃒⃒ *TS*3). *Thereafter*, *the derived session key is implicitly*

*structs and forwards message LAK*4 = {*D*1, *D*3, *D*4, *TS*4} *to the user’s MT*. *validated by checking if D*3*\** ≟ *D*3. *If this verification is successful*, *it con-* ℤ*K\** = *h* (*B*3*\*||ℕ*3*D*1), *B*3*\** = *h* (*γ||IDVi||B*2) *and D*2*\** = *h* (*IDg||IDVi||*ℤ*K*). *Here*, *session key* ℤ*K\* and security parameters B*3*\* and D*2*\* are derived as This is followed by implicit verification of the derived session key* ℤ*K\* via the*

*checking of whether D*2*\** ≟ *D*2 *as well as D*4*\** ≟ *D*4. *These session keys are then*

*deployed to encipher the exchanged packets to preserve their confidentiality and integrity*.

**Lemma 10**. *Known secret key attacks are thwarted in the proposed protocol*

**Proof**. *Suppose that parameters B*3*\**, *ℕ*3 *and D*1 *are captured by an ad-*

*D*2, *D*3, *D*2*\* and D*4*\**. *Here*, *D*1 = ℕ4*P*, *D*2 = h (*IDg||IDVi||*ℤ*K*), *D*3 = h (*B*3*\*|| IDVi||D*1*||D*2*||* SKg—Di ⃒⃒ *TS*3), *D*2*\** = *h* (*IDg||IDVi||*ℤ*K*), *D*4*\** = *h*(*γ||IDVi|| versary*. *The aim is to utilize these parameters to compose validation tokens A*1*\*||D*1*||D*2*||B*2*||TS*4), ℤ*K* = *h* (*B*3*\*||ℕ*3*D*1) *and IDVi* = *B*4⊕*h*(*B*2*\*||TS*1). *It is clear that although* ℤ*K can be computed from the captured parameters*, *the*

*IDg and DVi’s identity IDVi*. *On its part*, *token D*3 *still needs IDVi*, *D*2, SKg—Di *computation of validation tokens D*2 *and D*2*\* still require the gNB’s identity and valid timestamp TS*3. *Similarly*, *token D*4*\* still needs γ*, *IDVi*, *A*1*\**, *D*2, *B*2

*and valid timestamp TS*4. *Therefore*, *the authentication scheme is still secure in the face of active compromise of all the session key components*.

**Lemma 11**. *This scheme preserves backward and forward key secrecy*

**Proof**. *Suppose that an attacker has captured the current session keys* ℤ*K*

*previous and subsequent communication sessions*. *Here*, ℤ*K* = *h* (*B*3*\*|| and* ℤ*K\**. *Thereafter*, *an attempt is made to derive the session keys for the ℕ*3*D*1), ℤ*K\** = *h* (*B*3*\*||ℕ*3*D*1), *B*3*\** = *h* (*γ||IDVi||B*2), *D*1 = ℕ4*P*, *IDVi* = *B*4⊕*h* (*B*2*\*||TS*1), *γ* = *h* (*IDU||ℕ*2), *B*2*\** = *B*1*PVK*, *B*1 = ℕ3*P*, *B*2 = ℕ3*PUK*

*and B*4 = *IDVi*⊕*h* (*B*2*||TS*1). *Evidently*, *the computation of any valid session*

*key requires identities IDVi and IDU*, *random nonces ℕ*2, *ℕ*3 *and ℕ*4, *time-*

*stampTS*1, *gNB public key PUK and gNB private key PVK*.

Case 1: *Although the current session keys contain parameters B*3*\**, *ℕ*3 *and D*1, *they are protected by collision-resistant one-way hashing func- tion*. *As such*, *these parameters cannot be obtained due to the difficulty of reversing h(.*)*. Since parameter B*3*\* incorporates B*2, *it is evident that it is changed after every communication session in accordance with nonce ℕ*3. *Here*, *nonce ℕ*2 *and ℕ*4 *are only known to the user and DVi respectively*. *Therefore*, *the past as well as future session keys are still secure in the face*

4 4 1 3 3

*i* 2 3 A

*i* g—Di

*of active capture of the current session keys*.

*TS*2), *C*4 = h(*B*3*\*||IDVi\*||MA||B*1*||* SKg—Di *||TS*2), *D*1 = ℕ4*P*, *D*3 = h

Case 2: *Suppose that user*, *gNB and DV long term secrets are compro-*

(*B \*||IDV ||D ||D ||* SK

⃒⃒ *TS* ), *γ* = *h* (*ID ||ℕ* ), *D*

*i*

= h (*ID ||*

3 *i* 1 2

g—Di 3

*U* 2 2 *g*

*mised and the attacker obtains B*3*\**, *B*1 *and D*1 *through interception of*

*IDVi||*ℤ*K*), *IDVi* = *B*4⊕*h* (*B*2*\*||TS*1), *B*2*\** = *B*1*PVK*, *and D*4 = h(*γ\*||*

*private key PVK and shared key between the gNB and DVi* SKg—Di , *while IDVi||A*1*\*||D*1*||D*2*||B*2*\*||TS*4). *Evidently*, *derivation of D*3 *requires gNB* SKg—Di . *As such*, *gNB impersonation flops*. *the derivation of* {*C*3 *C*4} *requires shared key between the gNB and DVi*

Case 3: *Suppose that the adversary has captured previous session mes-*

*LAK*2 = {*B*3*\**, *C*3, *B*1, *C*4, *TS*2} *is required*. *However*, *devoid of keys PVK and* SKg—Di , *parameters C*3, *B*3*\* and C*4 *cannot be computed*. *In addition*, *sages and now wants to impersonate DVi*. *To accomplish this*, *message*

*valid timestamps and random nonces are required for these derivations*.

*Devoid of all these security tokens*, *message LAK*2 *can never be correctly constructed and hence IoT device impersonation fails*.

**Lemma 9**. *The communicating entities negotiate session key for traffic protection*

*derives session key* ℤ*K* = *h* (*B*3*\*||ℕ*3*D*1). *It then incorporates this session key* **Proof**. *During the login*, *authentication and key negotiation phase*, *DVi*

*exchanged message set* {*LAK*1, *LAK*2, *LAK*3, *LAK*4}. *However*, *the ad- versary needs to solve both ECDL and ECDH problems so as to obtain some of the session key parameters*.

**Lemma 12**. *Packet replays are prevented in this protocol*

**Proof**. *During the login*, *authentication and key negotiation phase*, *all the*

*TS*1, *TS*2, *TS*3 *and TS*4. *Here*, *LAK*1 = {*B*1, *B*3, *B*4, *B*5, *C*1, *C*2, *TS*1}, *LAK*2 = *exchanged messages LAK*1, *LAK*2, *LAK*3 *and LAK*4 *incorporate timestamps*

{*B*3*\**, *C*3, *B*1, *C*4, *TS*2}, *LAK*3 = {*ℕ*4, *D*2, *D*3, *TS*3} *and LAK*4 = {*D*1, *D*3, *D*4,

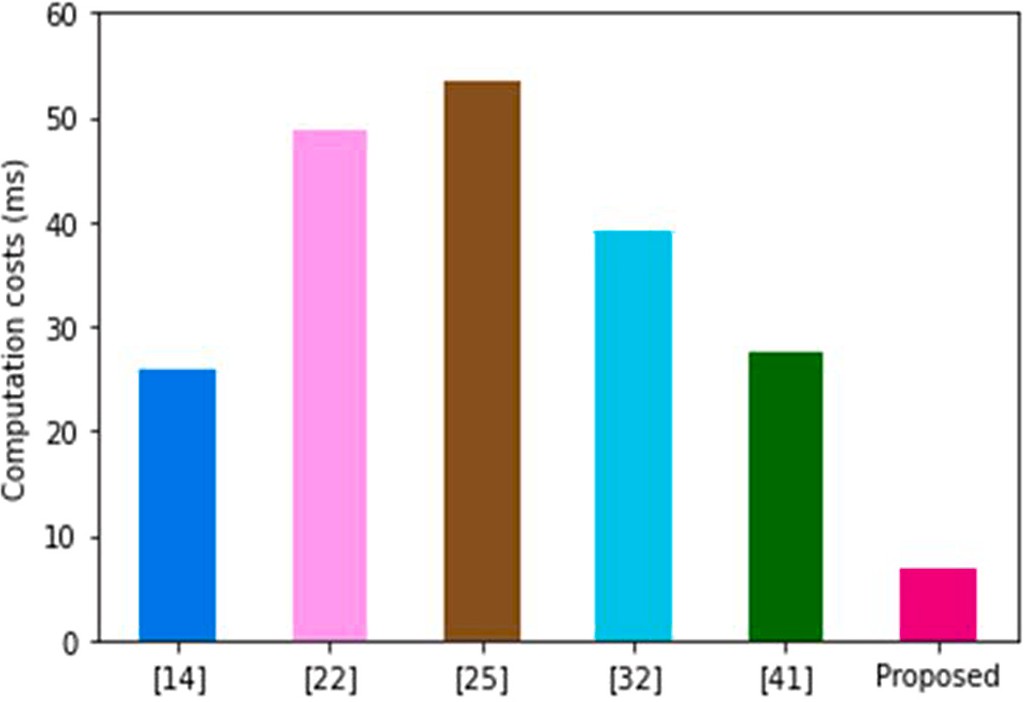
*TS*4}. *Upon receiving message LAK*1 *from the MT*, *the gNB validates TS*1

*against the delay tolerance ΔTS*, *while DVi checks the freshness of timestamp TS*2 *in message LAK*2 *using ΔTS*. *Similarly*, *upon receipt of message LAK*3 *from the DVi*, *the gNB validates the freshness of timestamp TS*3 *using delay tolerance threshold ΔTS*. *On its part*, *the MT validates timestamp TS*4 *in message LAK*4 *such that the session is terminated if this check fails*. *Conse- quently*, *any replayed message will have its timestamp TSReplay* > *ΔTS*. *Therefore*, *the authentication session using these replayed messages will be*

*i*

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Table 6** |  |  | **Table 7** |  |
| Computation costs. |  |  | Computation costs. |
| Scheme | Cost (ms) |  | Message | Cost (bits) |
| [[14](#_bookmark35)] | 25.78 |  | MT → gNB | 992 |
| [[22](#_bookmark43)] | 48.80 |  | LAK1 = {B1, B3, B4, B5, C1, C2, TS1} |  |
| [[25](#_bookmark46)] | 53.34 |  | B1= B3 = B4 = B5 = C1 = C2 =160; TS1 = 32 |  |
| [[32](#_bookmark53)] | 39.09 |  | gNB → DV1 | 672 |
| [[41](#_bookmark62)] | 27.66 |  | LAK2 = {B3\*, C3, B1, C4, TS2} |  |
| Proposed | 6.975 |  | B1 = B3\* = C3 = C4 =160; TS2 = 32 |  |
|  |  |  | DV1 → gNB | 480 |

LAK3 = {ℕ4, D2, D3, TS3}

ℕ4 = 128; D2 = D3 = 160; TS3 = 32

gNB → MT

LAK4 = {D1, D3, D4, TS4}

D1 = D3 = D4 = 160; TS4 = 32

512

**Total** 2656

**Table 8**

Communication costs.

|  |  |
| --- | --- |
| Scheme | Cost (bits) |
| [[14](#_bookmark35)] | 3104 |
| [[22](#_bookmark43)] | 3040 |
| [[25](#_bookmark46)] | 3488 |
| [[32](#_bookmark53)] | 3088 |
| [[41](#_bookmark62)] | 4008 |
| Proposed | 2656 |

**Fig. 5.** Computation costs comparisons.

*terminated*. *As such*, *the proposed scheme can effectively prevent packet replay attacks*.

**Lemma 13**. *This scheme can withstand offline password guessing attacks*

**Proof**. *Suppose that power analysis is utilized to launch side-channeling attacks upon which all the security tokens* {*Gen* (.), *A*2, *A*3, *Rep* (.), *ULi*, *h* (.), *νi*, *ɸ*, *P*} *in MT’s memory are obtained by an adversary*. *It is further assumed that user identity IDU has been captured by the attacker*.

Case 1: *The first goal of the adversary is to use the obtained parameters to derive user password PWU and parameter εi needed to launch a user masquerade attack*. *Among the captured parameters*, *it is only A*2, *A*3 *and*

*ɸ that contain PWU and parameter εi*. *Here*, *A*2 = h (*γ||σ*)⊕*A*1, *and A*3 =

h (*σ||A*1), *ɸ* = *ℕ*2⊕*h*(*IDU||εi*), *γ* = *h* (*IDU||ℕ*2), *σ* = *h* (*PWU||εi*) *and A*1

= h (*γ||IDg||MVT*). *Clearly*, *to obtaining PWU and εi from parameter σ is cumbersome due to the deployed collision-resistant one-way hashing*

*function*. *Similarly*, *deriving εi from parameter ɸ involves reversing the one-way hashing function*, *which is computationally infeasible*. *In addi-*

*Gen* (*β*) = (*εi*, *νi*). *tion*, *the derivation of εi requires not only νi but also biometric data β as in*

Case 2: *Suppose that the attacker has correctly guessed εi and is interested*

*check*. *Here*, *A*3*\** = *h* (*A*1⊕*h*(*γ||PWU||εi*)) *and A*1 = A2⊕ *h* (*γ||σ*). *As in confirming whether the derived password is valid through the A*3*\** ≟ *A*3 *such*, *this validation still requires parameter σ* = *h* (*PWU||εi*), *which is not*

*stored in the MT’s memory*. *Since the adversary is unable to obtain σ from*

*A*1 *owing to the one-way hashing function*, *offline guessing attack fails*.

# Performance evaluation

In this section, the proposed scheme is evaluated using computation, communication and the offered security features. These three parame- ters are chosen since they are the most common metrics for authenti- cation protocol evaluations. Towards the end of this section, experimentations are executed to investigate the variation of end to end

delays with the number of authentication requests emanating from IoT devices.

* 1. *Computation costs*

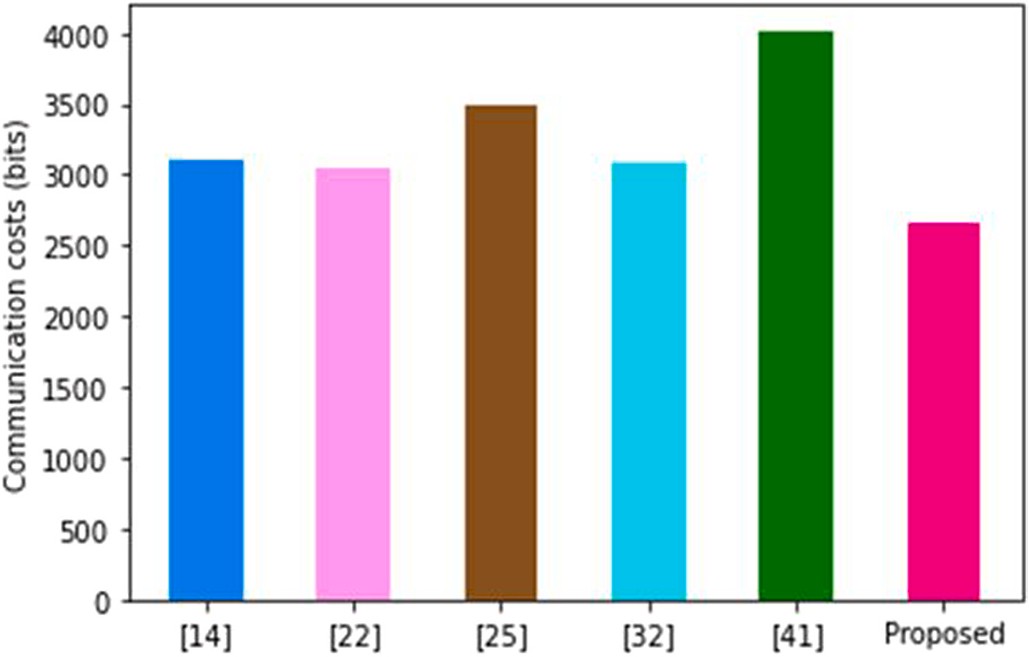
In the proposed scheme, the cryptographic operations executed during the login, authentication and key negotiation include fuzzy

(TEP). During the LAK process, 1TFE + 31TH + 6TEP operations are extraction (TFE), one-way hashing (TH) and ECC point multiplication which TH = 0.055 ms, TFE = 1.226 ms and TEP = 0.674 ms. As such, the executed. For fair comparisons, the values in Refs. [[6](#_bookmark27),[14](#_bookmark35)] are used in total computation cost for the proposed scheme is 6.975 ms. [Table 6](#_bookmark13)

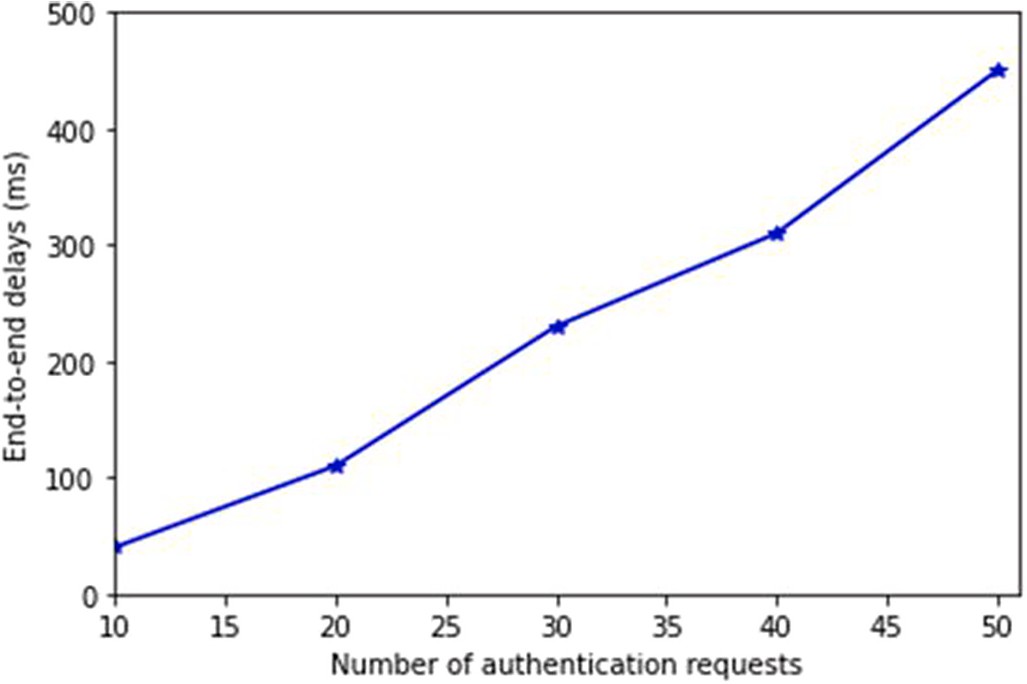
presents the computation costs of other related schemes.

As shown in [Fig. 5](#_bookmark15), the scheme in Ref. [[25](#_bookmark46)] has the highest compu- tation costs of 53.34 ms. This is followed by the protocols in Refs. [[14](#_bookmark35), [22](#_bookmark43),[32](#_bookmark53),[41](#_bookmark62)] in that order. On the other hand, the proposed scheme has the lowest computation overheads of only 6.975 ms. Since most of the IoT devices are limited in terms of processing and battery power, the scheme in Ref. [[25](#_bookmark46)] strains these devices and may cause rapid reduction in battery levels.

Consequently, the proposed scheme is the most unsuitable for



**Fig. 6.** Communication costs comparisons.

**Table 9**

Security features comparisons.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | [[22](#_bookmark43)] | [[32](#_bookmark53)] | [[14](#_bookmark35)] | [[25](#_bookmark46)] | [[41](#_bookmark62)] | Proposed |
| Security features |  |  |  |  |  |  |
| Mutual authentication | × | ✓ | ✓ | × | ✓ | ✓ |
| Session key agreement | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Anonymity | – | × | ✓ | – | ✓ | ✓ |
| Forward key secrecy | – | – | × | – | – | ✓ |
| Backward key secrecy | – | – | × | – | – | ✓ |
| Untraceability | – | – | ✓ | – | ✓ | ✓ |
| Attacks Resilience |  |  |  |  |  |  |
| Side-channeling | × | ✓ | ✓ | × | ✓ | ✓ |
| Privileged insider |  | ✓ | ✓ | – | ✓ | ✓ |
| Impersonation | ✓ | × | ✓ | ✓ | ✓ | ✓ |
| De-synchronization | – | – | ✓ | – | – | ✓ |
| Collusion | – | – | – | – | – | ✓ |
| Stolen verifier | – | – | ✓ | – | ✓ | ✓ |
| MitM | ✓ | × | – | ✓ | ✓ | ✓ |
| ESL | × | – | ✓ | × | ✓ | ✓ |
| Replay | ✓ | ✓ | – | ✓ | ✓ | ✓ |
| Known secret key | – | – | ✓ | – | – | ✓ |

Offline password guessing – – – – ✓ ✓

Key

√ = Supported

*5.4. Experimentations*

**Fig. 7.** End-to-end delays.

× = Not supported

= Not considered

deployment in an IoT environment. This is justified by its less strain on the processing and battery power levels of the IoT devices.

* 1. *Communication costs*

sages LAK1, LAK2, LAK3 and LAK4 are exchanged. Here, LAK1 = {B1, B3, B4, B5, C1, C2, TS1}, LAK2 = {B3\*, C3, B1, C4, TS2}, LAK3 = {ℕ4, D2, D3, During the login, authentication and key negotiation phase, mes-

TS3} and LAK4 = {D1, D3, D4, TS4}. Based on the values in Refs. [[6](#_bookmark27),[14](#_bookmark35)],

point = 320 bits, identity = 32 bits, hash output = 160 bits, random nonce = 128 bits and timestamps = 32 bits. [Table 7](#_bookmark14) gives the derivation the output sizes of the various operations are as follows: elliptic curve

of the communication costs of the proposed scheme.

Based on the values in [Table 7](#_bookmark14), the total communication overhead of the proposed scheme is 2656 bits. [Table 8](#_bookmark16) presents the communication costs of other related schemes.

Based on the graphs in [Fig. 6](#_bookmark18), the protocol in Ref. [[41](#_bookmark62)] has the highest communication overhead of 4008 bits. This is followed by the schemes in Refs. [[14](#_bookmark35),[22](#_bookmark43),[25](#_bookmark46),[32](#_bookmark53)] in that order. On the other hand, the proposed protocol has the least communication overhead of only 2656 bits.

As such, it makes the most efficient use of the network bandwidth. The lower communication costs in the proposed scheme is attributed to the usage of ECC, which provides the same level of security at smaller key sizes compared with techniques such as the Rivest-Shamir-Adleman (RSA). Therefore, it is the most suitable for deployment in 5G-IoT de- vices since these devices have limited communication capabilities.

* 1. *Security features*

To show that the proposed scheme offers many salient security and privacy features when compared with other related protocols, the comparisons in [Table 9](#_bookmark19) are presented. It is evident from [Table 9](#_bookmark19) that the protocol in Refs. [[22](#_bookmark43),[25](#_bookmark46)] offer only four security features and hence are the most insecure. This is followed by the scheme in Ref. [[32](#_bookmark53)] which provides five security features.

On the other hand, the protocols in Refs. [[14](#_bookmark35),[41](#_bookmark62)] offer eleven and twelve security features respectively. As such, they are more secure compared with the schemes in Refs. [[22](#_bookmark43),[25](#_bookmark46),[32](#_bookmark53)]. On the other hand, the proposed scheme offers seventeen security features and is therefore the most secure among all the other schemes.

In this sub-section, the experimentations that were executed to investigate the variations of End-to-End (E2E) delays with the number of authentication requests are presented. Here, a laptop with a 2.4 GHz Core i5-4210U CPU, 4 GB of RAM and running on Windows 10 Pro-64 bit is utilized. The programming language deployed is Python using PyCrypto library. As shown in [Fig. 7](#_bookmark20), the number of authentication re- quests is incremented from an initial value of 10 to a maximum of 50 requests.

It can be observed that as the number of authentication requests is increased, there is a corresponding increase in E2E delays. This is attributed to the increased processing that must be executed at the ter- minals for the surging number of authentication requests. It is clear that the graph of E2E against number of authentication requests is not entirely linear. This is because of other communication impairments such as congestions and packet losses that may necessitate the triggering of error correction techniques that cause further network delays.

# Conclusion

The 5G-IoT networks convey large amounts of private and sensitive data that can have serious consequences if compromised by attackers. To address this issue, numerous security protocols have been presented over the recent past. However, many security and privacy flaws have been identified in these schemes. In addition, some of the current schemes have poor performance owing to their extremely high communication and computation complexities. As such, the attainment of robust security at low communication and computation overheads is necessary but challenging. In this paper, a lightweight authentication, authorization and session key agreement scheme has been developed to address some of the issues in current security protocols. Its formal and informal security analyzes have shown existence of session key for traffic enciphering, as well as robustness under all the assumptions in the Canetti- Krawczyk (CK) threat model. In terms of performance, it has been shown to have the least communication and computation com- plexities. As such, the proposed protocol is reliable, efficient and prov- ably secure. Therefore, it is highly applicable in 5G-IoT communication environment where most of the devices are resource constrained. Future work lies in the assessment of the offered security features using other formal as well as informal threat models. There is also need for inno- vative techniques that can lead to further reduction in the communi- cation overheads of this scheme.

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