Signature-Based Authentication in Future Internet of Things (IoT) Applications

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Internet of Things (IoT)

- A “thing” in the IoT can be a person, animal or physical/virtual object with a unique identifier (IP address or device ID) that has the ability to transfer data (sensing information from surrounding area) via the Internet.
  - *Physical object:* Smartphone, camera, sensor, vehicle, drone, etc.
- The “Things” in IoT usually referes to IoT devices. IoT devices can perform remote sensing, actuating (making an action), and monitoring capabilities.
- A thing can be smart and thus, the thing can make a decision without human’s help (intervention).
  Majority of things are expected to be smart in the future.
- The objective of IoT is to integrate computer-based systems and the physical world for economic benefit and to improve accuracy and efficiency while reducing human involvement.
- An estimated 50 billion objects will be a part of IoT by 2020.

Internet of Things (IoT)

Table: IoT units installed based by category (millions of units)

Category	2016	2017	2018	2020
Consumer	3,963.00	5,244.30	7,036.30	12,863.00
Business: cross-industry	1,102.10	1,501	2,132.60	4,381.40
Business: vertical-specific	1,316.60	1,635.40	2,027.70	3,171
Grand total	6,381.80	8,380.60	11,196.60	20,415.40

Table: IoT endpoint spending by category (millions of dollars)

Category	2016	2017	2018	2020
Consumer	532,515	725,696	985,384	1,494,466
Business: cross-industry	212,069	280,059	372,989	567,659
Business: vertical-specific	634,921	683,817	736,543	863,662
Grand total	1379,505	1,689,572	2,094,881	2,925,787

Ref. Information Matters. The Business of Data and the Internet of Things (IoT). http://informationmatters.net/internet-of-things-statistics/. Accessed on August 2018.

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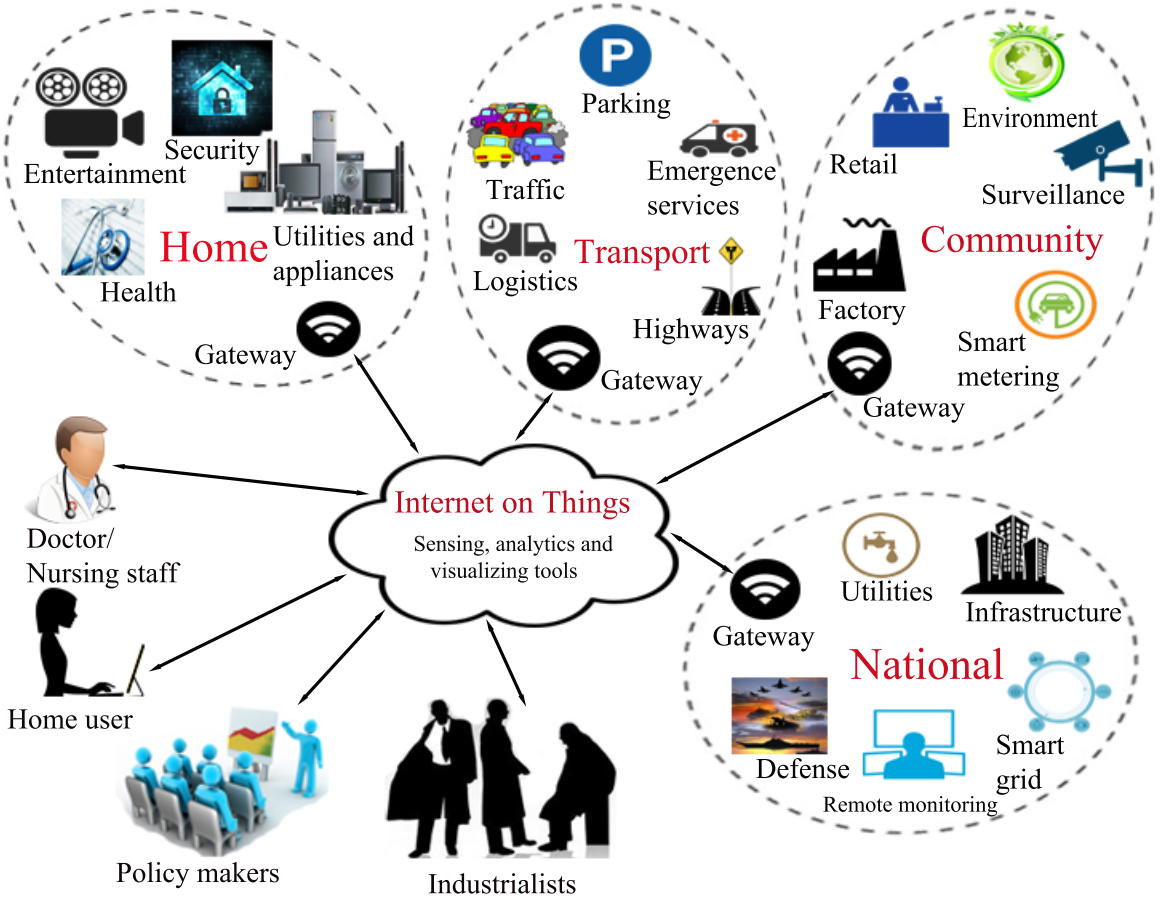
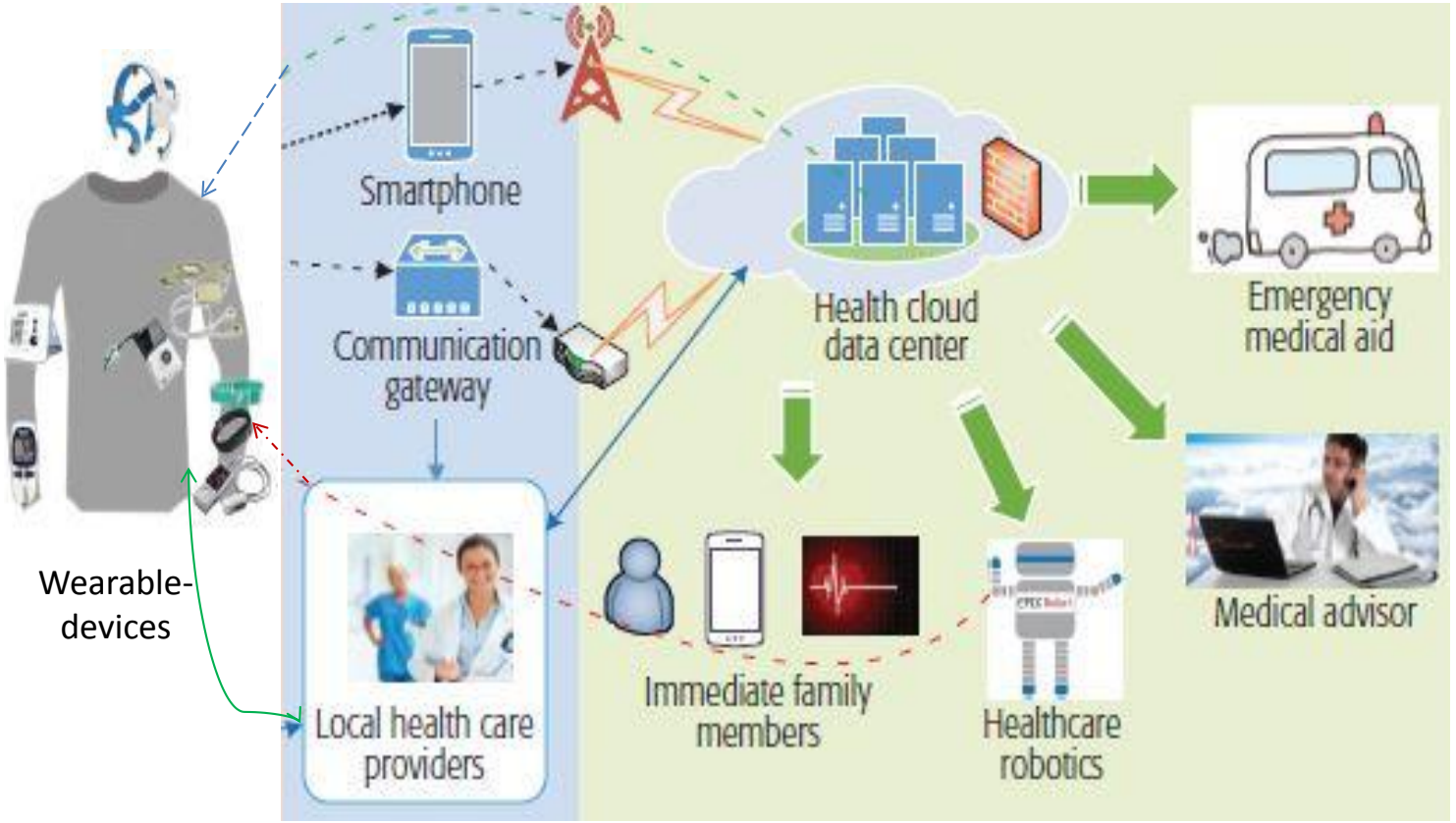


Figure: IoT authentication model

IoT authentication model

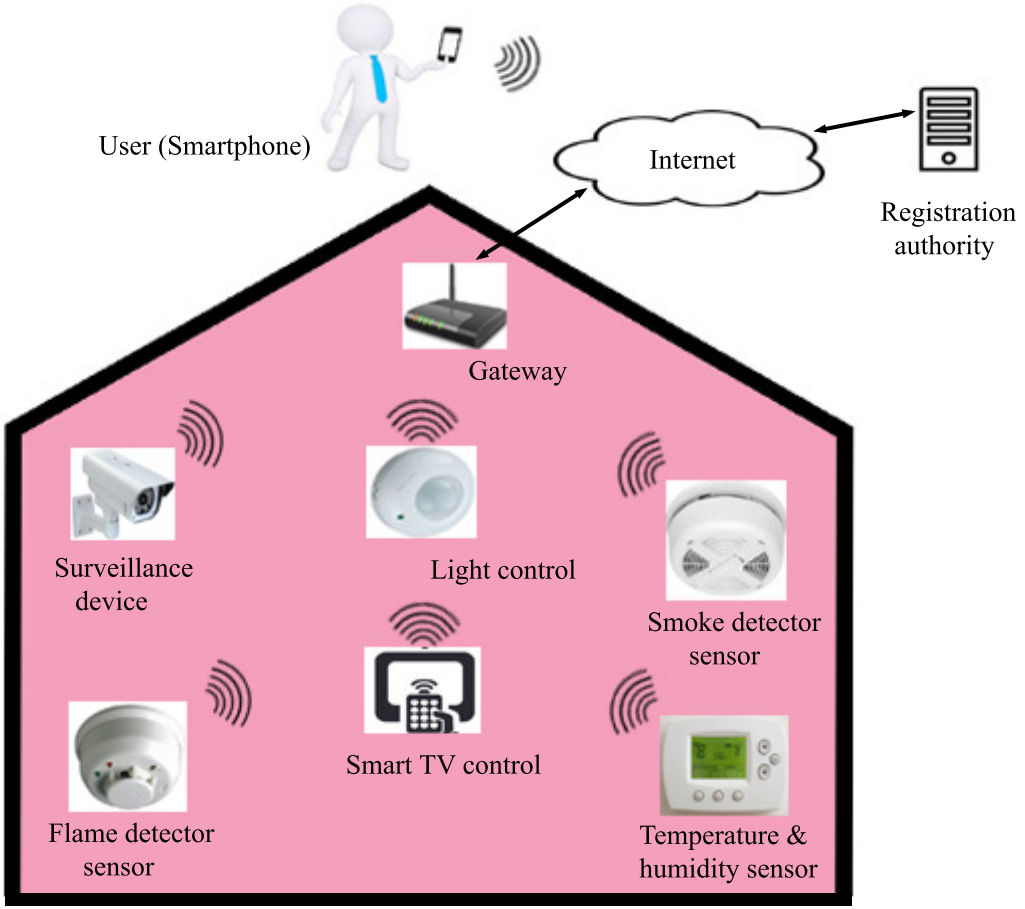
- IoT authentication model considers four different scenarios, i.e., Home, Transport, Community and National.
- All these scenarios have smart devices, such as sensors and actuators, which facilitate the day to day life of people.
- In the given scenarios, all smart devices are connected to the Internet through the gateway nodes (*GWN*s).
- Different types of users (for example, smart home user and doctor) can access the data of relevant IoT devices through the *GWN*.
- Mutual authentication between a user and a device through the *GWN* provides access to device data to the user.

IoT Applications: Healthcare



Jangirala Srinivas, Ashok Kumar Das, Neeraj Kumar, and Joel J. P. C. Rodrigues. "Cloud Centric Authentication for Wearable Healthcare Monitoring System," in **IEEE Transactions on Dependable and Secure Computing**, Vol. 17, No. 5, pp. 942-956, September/October 2020, DOI: 10.1109/TDSC.2018.2828306.

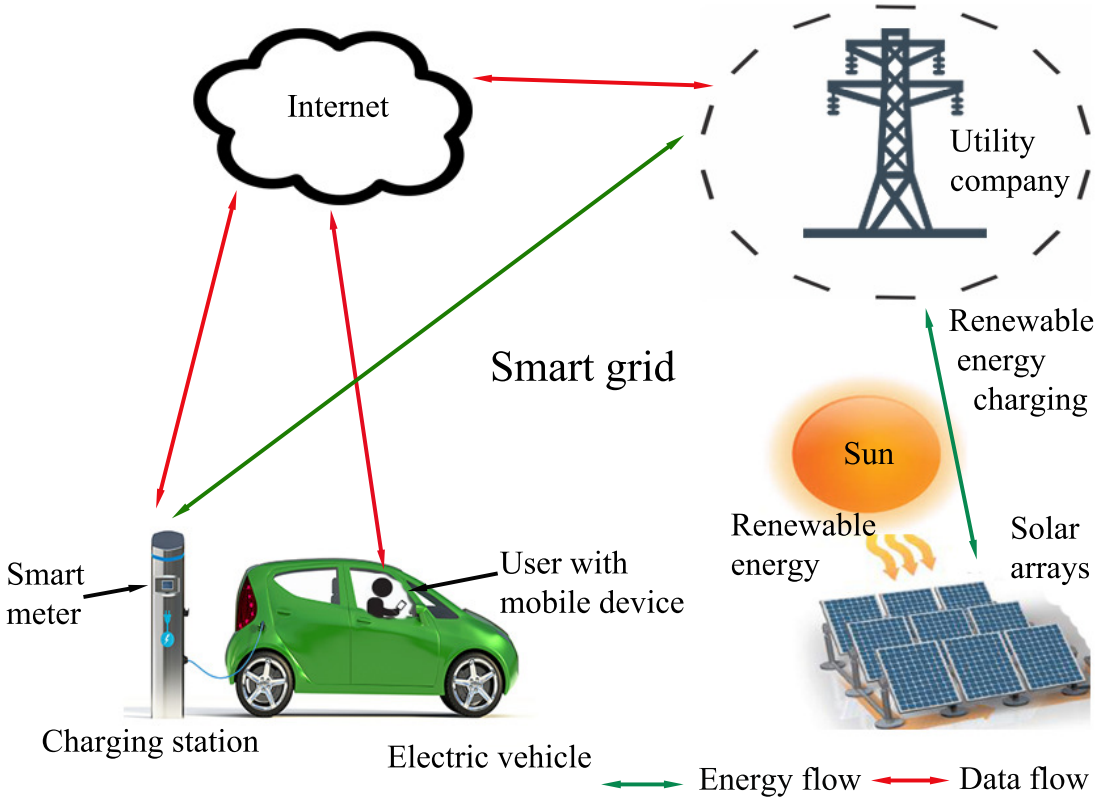
IoT Applications: Smart Home



Smart Home

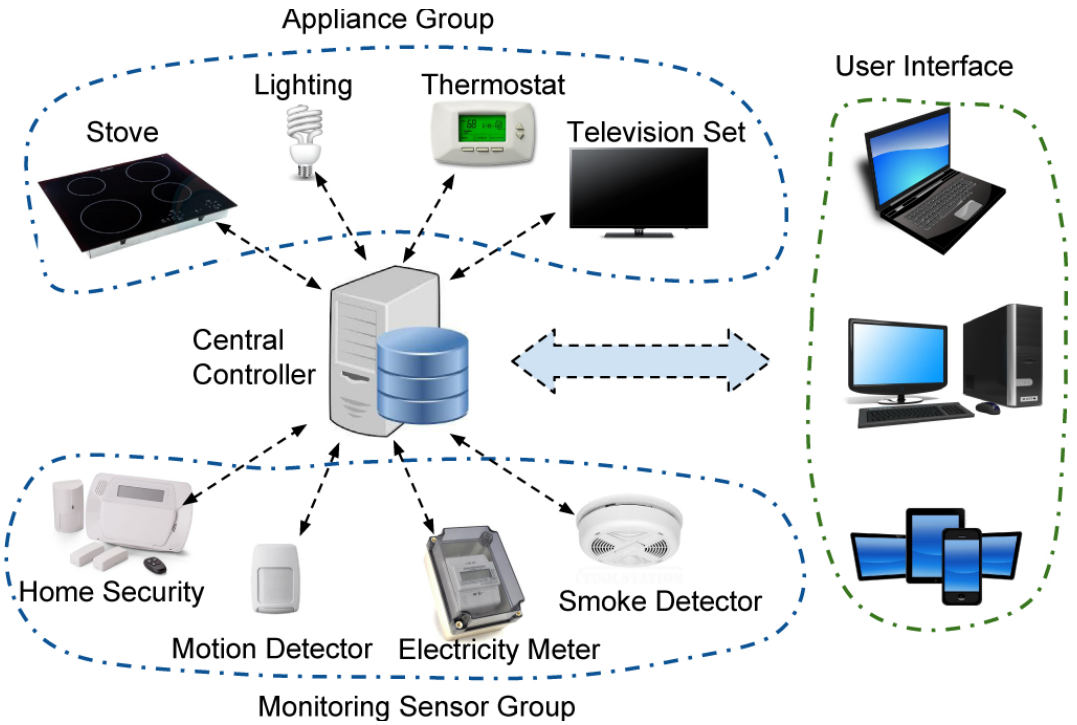
Mohammad Wazid, Ashok Kumar Das, Vanga Odelu, Neeraj Kumar, and Willy Susilo. "Secure Remote User Authenticated Key Establishment Protocol for Smart Home Environment," in **IEEE Transactions on Dependable and Secure Computing**, Vol. 17, No. 2, pp. 391-406, 2020, DOI: 10.1109/TDSC.2017.2764083.

IoT Applications: Renewable Energy-Based Smart Grid



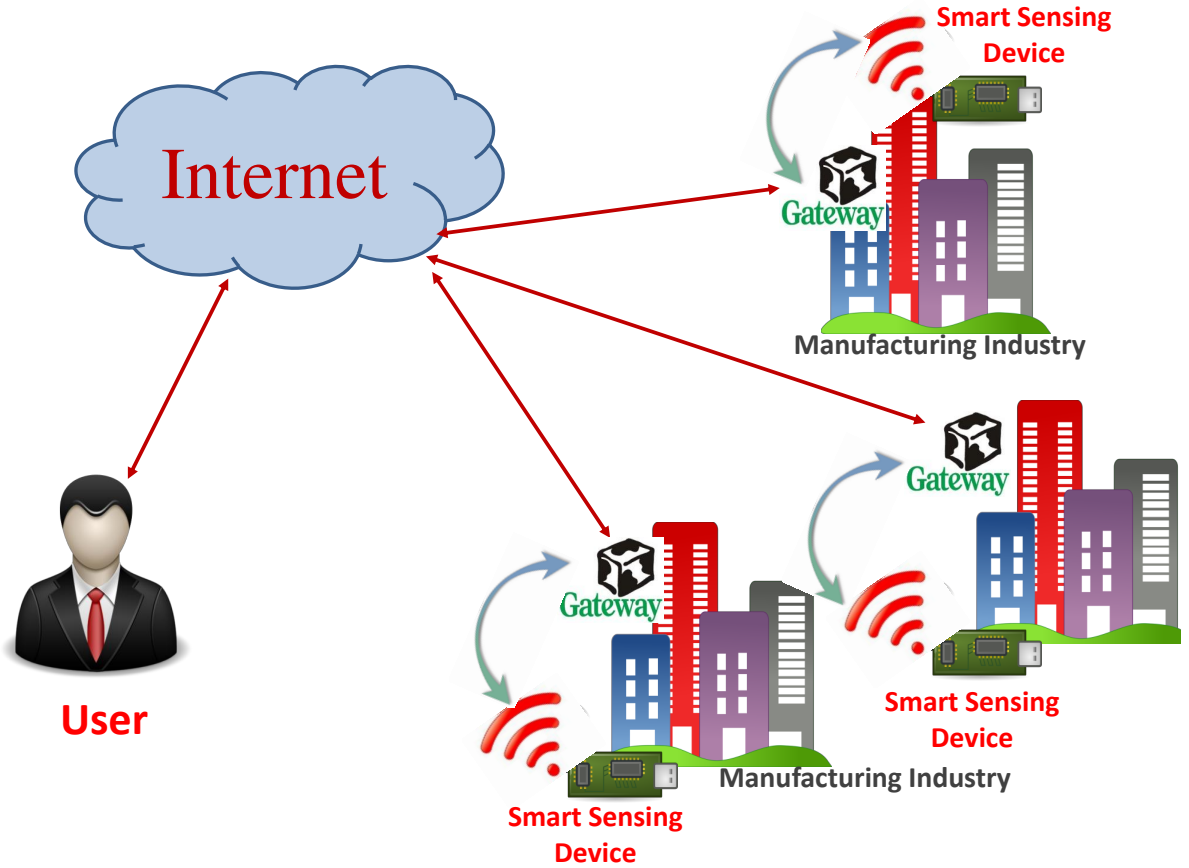
Mohammad Wazid, Ashok Kumar Das, Neeraj Kumar, and Joel J. P. C. Rodrigues. "Secure Three-factor User Authentication Scheme for Renewable Energy Based Smart Grid Environment," in **IEEE Transactions on Industrial Informatics**, Vol. 13, No. 6, pp. 3144-3153, 2017, DOI: 10.1109/TII.2017.2732999.

IoT Applications: Smart Home



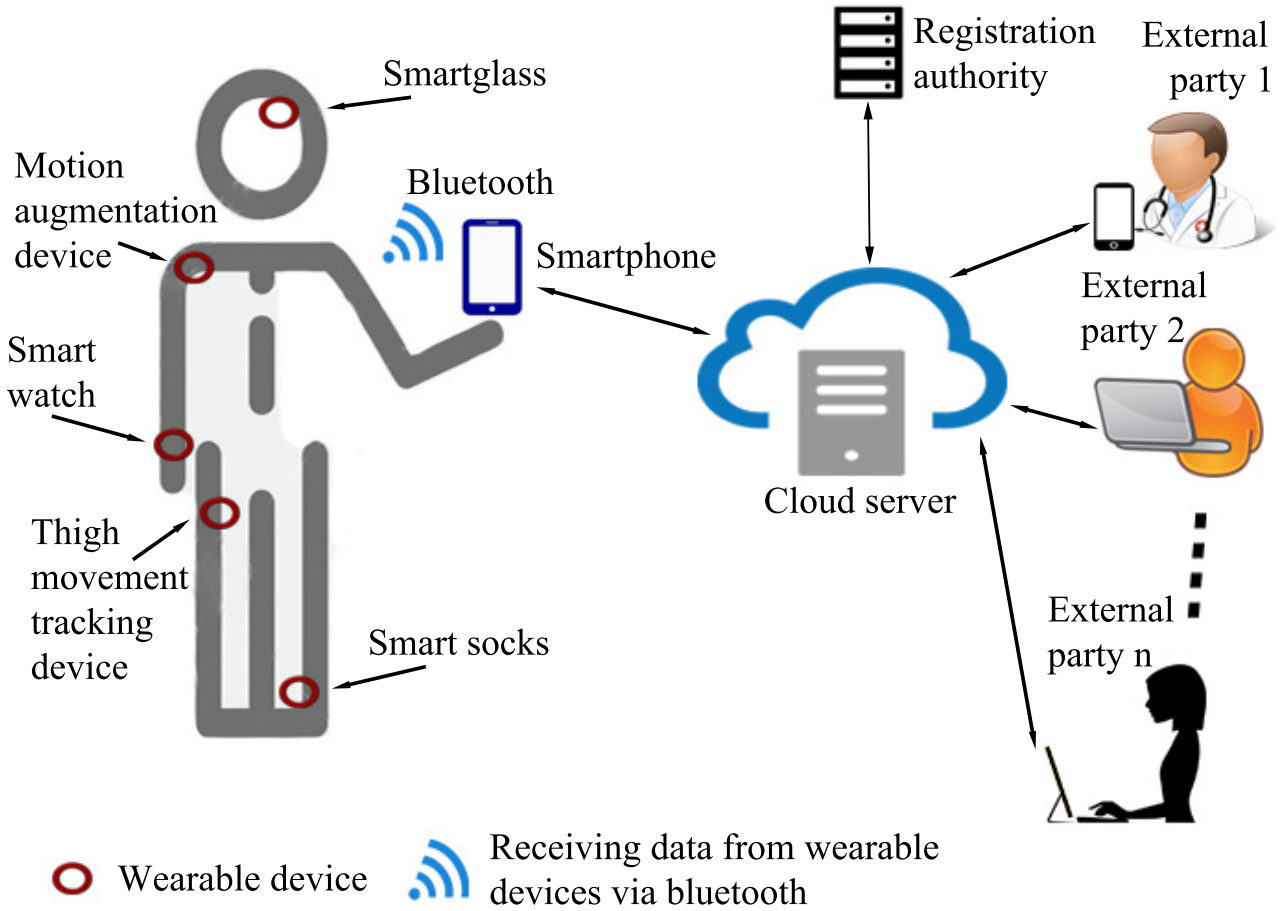
Mohammad Wazid, Ashok Kumar Das, Vanga Odelu, Neeraj Kumar, Mauro Conti, and Minho Jo. "Design of Secure User Authenticated Key Management Protocol for Generic IoT Network," in *IEEE Internet of Things Journal*, Vol. 5, No. 1, pp. 269-282, 2018.

IoT Applications: Industrial IoT



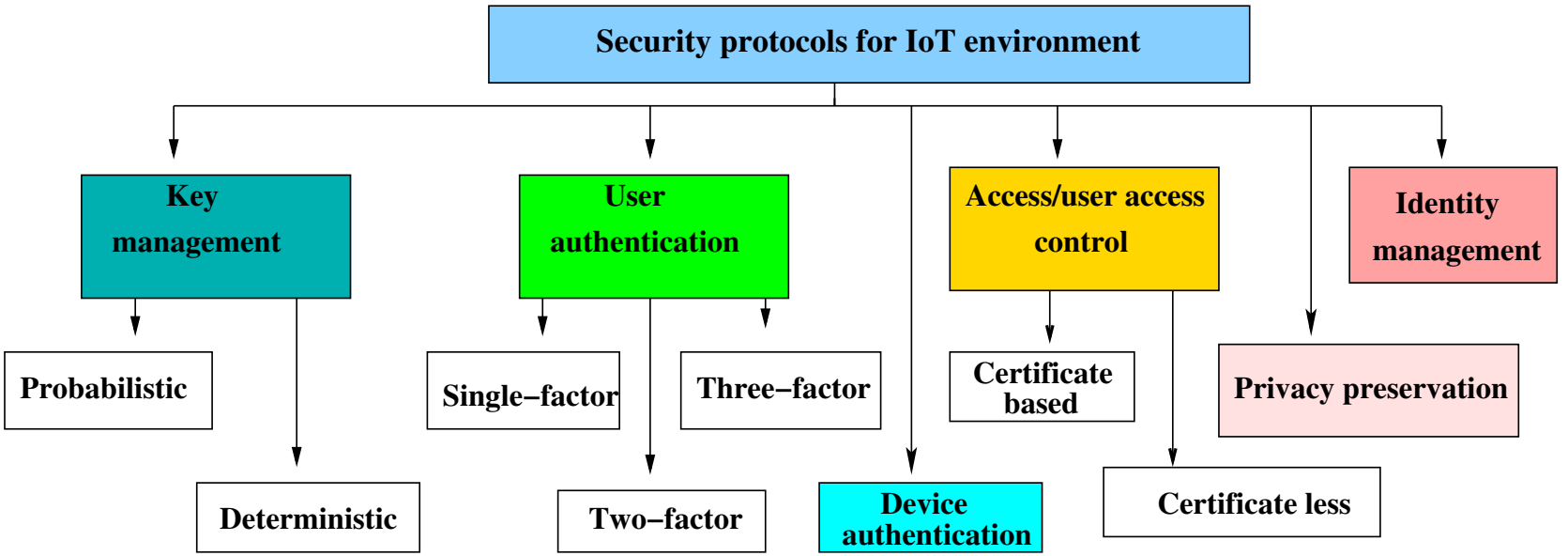
Jangirala Srinivas, Ashok Kumar Das, Mohammad Wazid, and Neeraj Kumar. "Anonymous Lightweight Chaotic Map-Based Authenticated Key Agreement Protocol for Industrial Internet of Things," in *IEEE Transactions on Dependable and Secure Computing*, ol. 17, No. 6, pp. 1133-1146, 2020, DOI: 10.1109/TDSC.2018.2857811.

IoT Applications: Healthcare



Ashok Kumar Das, Mohammad Wazid, Neeraj Kumar, Muhammad Khurram Khan, Kim-Kwang Raymond Choo, and YoungHo Park. "Design of Secure and Lightweight Authentication Protocol for Wearable Devices Environment," in **IEEE Journal of Biomedical and Health Informatics (Formerly, IEEE Transactions on Information Technology in Biomedicine)**, Vol. 22, No. 4, pp. 1310-1322, 2018.

Taxonomy of security protocols in IoT



Ashok Kumar Das, Sherali Zeadally, and Debiao He. "Taxonomy and Analysis of Security Protocols for Internet of Things," in *Future Generation Computer Systems (Elsevier)*, Vol. 89, pp. 110-125, 2018, DOI: 10.1016/j.future.2018.06.027.

Security requirements in IoT environment

- **Authentication:** It involves authentication of sensing devices, users and gateway nodes before allowing access to a restricted resource, or revealing crucial information.
- **Integrity:** The message or the entity under consideration must not be changed to ensure integrity.
- **Confidentiality:** Confidentiality or privacy of the wireless communication channel protects from the unauthorized disclosure of information.
- **Availability:** The relevant network services should be made available to authorized users even under denial-of-service attacks on the system.
- **Non-repudiation:** It aims to prevent a mischievous entity from hiding his/her actions.
- **Authorization:** It confirms that only the legitimate IoT sensing (smart) devices can supply information to network services.
- **Freshness:** It confirms that the information is fresh and the old messages cannot be replayed by any adversary.
- Apart from the above security requirements, the following two important security properties should also be satisfied:
  - **Forward secrecy:** If an IoT sensing node quits the network, any future messages after its exit must be prohibited.
  - **Backward secrecy:** If a new IoT sensing node is added in the network, it must not read any previously transmitted message.

Security attacks in IoT environment

- **Replay attack:** A replay attack is one in which an adversary, $\mathcal{A}$ attempts to mislead another authorized entity by reusing the information during the transmission.
- **Man-in-the-middle attack:** Under such an attack, $\mathcal{A}$ intercepts the transmitted messages and tries to change/delete/modify the contents of the messages delivered to the recipients.
- **Stolen-verifier attack:** This attack can occur if the *GWN* in the IoT network stores any verifier/password table for user/device verification. In such an attack, $\mathcal{A}$ can steal a user's credentials such as identity or password from the table.
- **Stolen/lost smart card attack:** If $\mathcal{A}$ has a lost/stolen smart card, he/she can extract all the credentials stored into its memory by using techniques such as power analysis attacks. Using the extracted information, $\mathcal{A}$ can then derive the secret credentials.
- **Password guessing attack:** In a password-based scheme, $\mathcal{A}$ may attempt to guess the password of a legal registered user either online or offline mode with the help of the eavesdropped messages and also stored credentials in the system or a user's smart card (mobile device).

Security attacks in IoT environment (Cont...)

- **Password change attack:** Under this attack, $\mathcal{A}$ may try to change the password of an authorized registered user.
- **Denial-of-Service attack:** A Denial-of-Service (DoS) attack is any event that prevents a system's or network' capability to perform its expected function.
- **Privileged-insider attack:** In this kind of attack, a trusted user within the organization (also known as an insider) can act as a privileged-insider attacker.
- **Impersonation attack:** In an impersonation attack, an attacker may attempt to falsify a fake message to defraud other recipient entities in a network on behalf of a sending entity.
- **Resilience against smart device physical capture attack:** In IoT environment, except the *GWN* the IoT sensing devices are not physically protected. Hence, there is a possibility of physical capturing of the sensing devices by an attacker $\mathcal{A}$. $\mathcal{A}$ can then use the extracted information stored in those captured sensing devices to compromise communication between other non-compromised sensing devices.

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- Sravani Challa, Mohammad Wazid, Ashok Kumar Das, Neeraj Kumar, Alavalapati Goutham Reddy, Eun-Jun Yoon, and Kee-Young Yoo, "Secure Signature-Based Authenticated Key Establishment Scheme for Future IoT Applications," in **IEEE Access**, Vol. 5, pp. 3028-3043, 2017. **[This article is one of the top 50 most frequently downloaded documents for Popular Articles (May-June 2017)]**

Threat model

- We follow the widely-accepted Dolev-Yao threat (DY) model [1].
- Under the DY model, communication between two entities is performed over a public channel.
- An adversary can then have an opportunity to eavesdrop, modify or delete the content of the messages being transmitted.
- An adversary can physically capture one or more sensing devices in IoT, and can extract all the sensitive information stored in the captured devices using the power analysis attacks [2], [3].

[1] D. Dolev and A. Yao, "On the security of public key protocols," ***IEEE Transactions on Information Theory***, vol. 29, no. 2, pp. 198–208, 1983.
[2] T. S. Messerges, E. A. Dabbish, and R. H. Sloan, "Examining smart-card security under the threat of power analysis attacks," ***IEEE Transactions on Computers***, vol. 51, no. 5, pp. 541–552, 2002.
[3] P. Kocher, J. Jaffe, and B. Jun, "Differential power analysis," in 19th Annual IACR Crypto Conference (Advances in Cryptology) - ***CRYPTO'99***, LNCS, vol. 1666, Santa Barbara, California, USA, 1999, pp. 388–397.

Contributions in this work

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- An authentication model for IoT is presented and the security challenges involved and its requirements are discussed.
- A secure signature-based authentication and key agreement scheme has been proposed to address these issues.
- A formal security analysis using the widely-used Burrows-Abadi-Needham logic (BAN logic) and an informal security analysis have been presented to prove that the scheme is secure.
- Simulation using the broadly-accepted Automated Validation of Internet Security Protocols and Applications (AVISPA) tool for the formal verification of the scheme's security has also been provided.
- Using NS2 simulator, the scheme's impact on network performance parameters has been measured for practical demonstration of the scheme.
- Finally, it has been shown that the scheme is also efficient in terms of communication and computation costs.

Notations

Symbol	Description
GWN	Gateway node
SD_j	j^{th} sensing device
ID_j	SD_j's identity
U_i	i^{th} user
SC_i	U_i's smart card
ID_i	U_i's identity
PW_i	U_i's password
BIO_i	U_i's personal biometrics template
σ_i	Biometric secret key
τ_i	Biometric public reproduction parameter
t	Error tolerance threshold used by fuzzy extractor
$Gen(\cdot)$	Probabilistic generation procedure used by fuzzy extractor
$Rep(\cdot)$	Deterministic reproduction procedure used by fuzzy extractor
$h(\cdot)$	Collision-resistant one-way cryptographic hash function

Notations (Continued...)

Symbol	Description
p	A large prime number
Z_p	$Z_p = \{0, 1, \cdots, p-1\}$, a prime finite field
E_p	An elliptic curve over prime field Z_p
$P = ((P)_x, (P)_y)$	An elliptic curve point in elliptic curve E_p, $(P)_x$ and $(P)_y$ are x and y coordinates of P, respectively
$k.P$	Elliptic curve point multiplication; $k \in Z_p^*$ being a scalar and $P \in E_p$
d	private key of involved entities
Q	$Q = d.P$, public key of involved entities
T_i, T_s	Current system timestamps
ΔT	Maximum transmission delay
sk_{ij}	Session key between U_i and SD_j
$\oplus, \|\|$	Bitwise XOR and concatenation operations, respectively

Elliptic Curve Cryptography (ECC)

Elliptic curves over modulo a prime $GF(p)$

Let $p > 3$ be a prime. The elliptic curve $y^2 = x^3 + ax + b$ over Z_p is the set $E_p(a, b)$ of solutions $(x, y) \in E_p(a, b)$ to the congruence

$$y^2 \equiv x^3 + ax + b \pmod{p},$$

where $a, b \in Z_p$ are constants such that $4a^3 + 27b^2 \neq 0 \pmod{p}$, together with a special point $\mathcal{O}$ called the point at infinity (or zero point).

Properties of Elliptic Curves

- An elliptic curve $E_p(a, b)$ over Z_p (p prime, $p > 3$) will have roughly p points on it.
- More precisely, a well-known theorem due to Hasse asserts that the number of points on $E_p(a, b)$, which is denoted by $\#E$, satisfies the following inequality:

$$p + 1 - 2\sqrt{p} \leq \#E \leq p + 1 + 2\sqrt{p}.$$

- In addition, $E_p(a, b)$ forms an abelian or commutative group under addition modulo p operation.

Elliptic Curve Cryptography (ECC)

- **Point addition on elliptic curve over finite field** $GF(p)$
  If $P = (x_P, y_P)$ and $Q = (x_Q, y_Q)$ be two points on elliptic curve $y^2 = x^3 + ax + b \pmod p$, $R = (x_R, y_R) = P + Q$ is computed as follows:

$$x_R = (\lambda^2 - x_P - x_Q) \pmod p,$$
$$y_R = (\lambda(x_P - x_R) - y_P) \pmod p,$$
$$\text{where } \lambda = \begin{cases} \frac{y_Q - y_P}{x_Q - x_P} \pmod p, \text{ if } P \neq -Q \\ \frac{3{x_P}^2 + a}{2y_P} \pmod p, \text{ if } P = Q. \end{cases}$$

- **Scalar/point multiplication on elliptic curve over finite field** $GF(p)$
  If $P = (x_P, y_P)$ be a point on elliptic curve $y^2 = x^3 + ax + b \pmod p$, then $5P$ is computed as $5P = P + P + P + P + P$.

Elliptic Curve Cryptography (ECC)

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Definition (Elliptic Curve Discrete Logarithm Problem (ECDLP))

Let $E_p(a, b)$ be an elliptic curve modulo a prime p. Given two points $P \in E_p(a, b)$ and $Q = kP \in E_p(a, b)$, for some positive integer k, where $Q = kP$ represent the point P on elliptic curve $E_p(a, b)$ be added to itself k times. Then the elliptic curve discrete logarithm problem (ECDLP) is to determine k given P and Q.

Definition (Elliptic Curve Decisional Diffie-Hellman Problem (ECDDHP))

Let $E_p(a, b)$ be an elliptic curve and $G \in E_p(a, b)$ be a base point. The elliptic curve decisional Diffie-Hellman problem (ECDDHP) is defined as follows. Given a quadruple $(G, u.G, v.G, w.G)$, decides whether $w = u.v \pmod{p}$.

Biometrics and Fuzzy Extractor

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Definition

The fuzzy extractor is a tuple $(\mathcal{M}, l, t)$, which is composed of the following two algorithms, called *Gen* and *Rep*:

- **Gen:** It is a probabilistic algorithm, which takes a biometric information $B_i \in \mathcal{M}$ as input, and then outputs a secret key $\sigma_i \in \{0,1\}^l$ and a public reproduction parameter τ_i, where $Gen(B_i) = \{\sigma_i, \tau_i\}$.
- **Rep:** This is a deterministic algorithm, which takes a noisy biometric information $B_i' \in \mathcal{M}$ and a public parameter τ_i and t related to B_i, and then it reproduces (recovers) the biometric key data σ_i. In other words, we have $Rep(B_i', \tau_i) = \sigma_i$ provided that the condition: Hamming distance $d(B_i, B_i') \leq et$ is met.

One of the estimations on error tolerance threshold values provided by Cheon *et al.* is as follows: If the Hamming distance between the original biometric template B_i and current biometric template B_i' is h_T and the number of bits in input biometric is n_b, we then have $et = \frac{h_T}{n_b}$.

Biometrics and Fuzzy Extractor

- The probability to guess the biometric key data $\sigma \in \{0,1\}^l$ by an attacker is approximately $\frac{1}{2^l}$, where $l = m - 2\log(\frac{1}{\epsilon}) + O(1)$, where ϵ is the statistical distance between two given probability distributions, and m is the min-entropy given as follows. the min-entropy $H_\infty(A)$ of a random variable A is $-log(max_a Pr[A = a])$.

Vanga Odelu, Ashok Kumar Das, and Adrijit Goswami. "A Secure Biometrics-Based Multi-Server Authentication Protocol using Smart Cards," in **IEEE Transactions on Information Forensics and Security**, Vol. 10, No. 9, pp. 1953 - 1966, 2015, DOI: 10.1109/TIFS.2015.2439964. **[This article is one of the top 50 most frequently downloaded documents for Popular Articles (June - November 2015)]**

System Setup Phase

- *GWN* chooses a non-singular elliptic curve E_p over $GF(p)$ and a base point P of order n as large as the prime p.
- *GWN* also picks its private key d_{GWN} and computes the corresponding public key $Q_{GWN} = d_{GWN}.P$.
- *GWN* then chooses a collision-resistant one-way cryptographic hash function $h(\cdot)$, fuzzy extractor functions $Gen(\cdot)$ and $Rep(\cdot)$.
- The system parameters $\{E_p(a, b), p, P, h(\cdot), Q_{GWN}, Gen(\cdot), Rep(\cdot), t\}$ are made public, whereas d_{GWN} is kept secret by *GWN*.

Sensing Device Registration Phase

All the sensing devices in IoT are registered offline by the *GWN* as follows.

- For each device SD_j, the *GWN* chooses a unique identity ID_j and a unique private key d_j, and calculates the corresponding public key $Q_j = d_j.P$. It further computes $RID_j = h(ID_j \| d_j)$.
- The *GWN* pre-loads $\{ID_j, d_j, RID_j\}$ in the memory of SD_j. Furthermore, the *GWN* stores $\{ID_j, RID_j, Q_j\}$ in its database, and then makes Q_j as public.

User Registration Phase

User (U_i)	Gateway node (GWN)
Select identity ID_i, private key d_i. Compute public key $Q_i = d_i.P$ $RID_i = h(d_i \| ID_i)$. $\langle RID_i \rangle \xrightarrow{}$ (Secure channel)	Compute $R_i = h(RID_i \| d_{GWN})$. $\xleftarrow{\langle \text{Smart Card}\{R_i\} \rangle}$ (Secure channel)
Select password PW_i. Imprint personal biometric Bio_i. Compute $Gen(Bio_i) = (\sigma_i, \tau_i)$, $RPW_i = h(PW_i \| d_i \| ID_i \| \sigma_i)$, $R_i^* = R_i \oplus h(ID_i \| PW_i \| \sigma_i)$, $d_i^* = d_i \oplus h(ID_i \| \sigma_i)$. Insert $\{d_i^*, RPW_i, \tau_i, t, h(\cdot)$, $Gen(\cdot)$ and $Rep(\cdot)\}$ into smart card. Replace R_i with R_i^* in smart card.	