A Survey on Hardware-based Security Mechanisms for Internet of Things

ALIREZA SHAMSOSHOARA, ASHWIJA KORENDA, and FATEMEH AFGHAH, School of Informatics, Computing, and Cyber Systems, Northern Arizona University
SHERALI ZEADALLY, College of Communication and Information, University of Kentucky

The vast areas of applications for IoTs in future smart cities, industrial automation, smart transportation systems, and smart health facilities represent a thriving surface for several security attacks with enormous economic, environmental and societal impacts. This survey paper presents a review of several security challenges of emerging IoT networks and discusses some of the attacks and their countermeasures based on different domains in IoT networks. Most conventional security solutions for IoT networks are adopted from communication networks while noting the particular characteristics of IoT networks such as the huge number of nodes, heterogeneity of the network, and the limited energy, communication, and computation of the nodes, these conventional security methods are not really adequate. One important challenge toward utilizing common secret key-based cryptographic methods in very large scale IoT networks is the problem of secret key generation, distribution, and storage in IoT devices and more importantly protecting these secret keys from physical attacks. Physically unclonable functions (PUFs) are recently utilized as a promising hardware security solution for identification and authentication in IoT networks. Since PUFs extract the unique hardware characteristics, they potentially offer an affordable and practical solution for secret key generation. However, several barriers limit the applications of different types of PUFs for key generation purposes. We discuss the advantages of PUF-based key generation methods, review the state-of-the-art techniques in this field and propose a reliable PUF-based solution for secret key generation using resistive random-access memories (RERAMs) embedded in IoTs.

1 INTRODUCTION

Wireless communication technologies have managed to imprint itself into everyone’s lives through emerging Internet of Things (IoTs). IoT allows interconnection of billions of objects from tiny sensors to automobiles, and smart phones to factories and hospitals. IoT systems currently impact different aspects of people daily life. Various kinds of information

CCS Concepts: • Security and privacy → Security in hardware; • Computer systems organization → Embedded and cyber-physical systems.

Additional Key Words and Phrases: security, hardware-based security, IoT, physical unclonable functions (PUFs), memory-based PUFs, key generation, authentication

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Authors’ addresses: Alireza Shamsoshoara, alireza_shamsoshoara@nau.edu; Ashwija Korenda, ashwijakorenda@nau.edu; Fatemeh Afgah, Fatemeh.Afgahi@nau.edu, School of Informatics, Computing, and Cyber Systems, Northern Arizona University, Flagstaff, Arizona. Sherali Zeadally, szeadally@uky.edu, College of Communication and Information, University of Kentucky, Lexington, Kentucky.

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including location information, medical information, and etc are constantly gathered by sensors and different electronic and tracking devices [17]. Some examples include using smart watches to set the credit cards with the cell phone’s NFC interface to stimulate a transaction protocol and reduce the required time for shopping [54]; using IoT-based remote health monitoring systems to gather information from patients in a short time and inform the physicians to take timely actions [99]. Figure 1 demonstrates various applications of IoT systems in our day-to-day life. While IoT networks have improved the quality of life in many levels and opened up a path for several new services, due to the power and computing limitation, high mobility, and the dynamic nature of the network, security threats and attacks can rapidly propagate throughout the entire network [83]. One key challenge in IoT networks is the lack of a unified security, identification and authentication standard, while new products and technologies come to market every day without paying enough attention to the potential security threats. Besides the security challenges, there are several other concerns regarding the large scale IoT networks in terms of data fusion and data management, complexity, spectrum scarcity, and so on [3, 51, 53, 145–147, 150, 169, 170, 189]. Moreover, several recent IoT technologies are still based on IPV4 for addressing which compromises the scalability of these networks.

![Fig. 1. Some examples of IoT applications](image)

The attacks on IoTs are usually intentional attacks by hackers who silently eavesdrop the communications between the nodes and gather confidential information or intrude themselves in the network and tamper with the sensitive information that can potentially result in failure of the entire system. According to Symantec [123], cyber-criminals progressively target IoT devices since they are developing and expanding rapidly. The number of IoT attacks increased by 600% in 2017 compared to 2016 [123]. In 2018, there was an increase of 217.5% from 2017 with 32.7 million IoT attacks. Ransomware is one of the growing malwares, in which the attacker uses Bitcoin or prepaid credit cards to demand
money, where they do not need to decrypt the public or private keys for stealing cards information [117, 172]. For instance, in the earlier months of 2017, a number of individuals and businesses around the world were affected by two huge ransomware attacks, followed by a variant called “Wanacry” which affected 300,000 computers. Petya is another version of the ransomware attack, which exploited the existence of a third party software to spread and grow itself in the networks [67, 139, 181]. The prevalence of this malware started from Ukraine, where 12,500 computers were affected. According to Microsoft, this malware has been outspread by using a third-party application [67]. Dyn cyber attack in 2016 that caused distributed denial of service (DDoS) for several Internet platforms and services in Europe and North America was also a result of insufficient security at the IoT nodes [47]. These attacks have even penetrated into remote health monitoring systems. An article published in the Journal of the American College of Cardiology in February 2018, confirms that cardiac devices can be attacked by hackers leading to severe consequences or even death in some cases [8].

There are several factors contributing to the immense security vulnerability of IoTs including the limited energy available at IoT nodes, their low computational capability, the huge number of available nodes in the network as well as the heterogeneous nature of the network [137]. These characteristics, in particular, the number of connected devices, often result in inefficient performance of conventional security mechanisms. By 2020, it is expected that about 31 billion IoT devices will be connected to the Internet, which drastically increases the need for advanced security mechanisms for IoT. These devices need to communicate with each other to transmit the data they collected or received from other devices and intelligently respond and react to the received information. Therefore, it is crucial that information is received from and sent to an authenticated user. Figure 2a shows a few examples of IoT devices connected to the Internet, which can be controlled using the users’ cellphones or smartwatches. If these devices are hacked, it can interrupt the users’ daily life. For example, the user may not be able to use his/her car or even the hacker can induce a heart attack for the users with implanted pacemakers. Figure 2b shows an example of an attack on an IoT device that allows remote control over a smart home, a car navigation system and a remote heart monitoring system for a patient with a pacemaker. The goal of the attacker is to interrupt the communications between different IoT nodes and to manipulate the data being sent, by extracting the cryptographic key. In such scenarios, tamper detection circuits are needed to prevent the attacks, but these are infeasible in low-power IoT nodes.

The security challenges in IoTs can be broadly classified into identification, authentication, encryption, confidentiality, jamming, cloning, hijacking, and privacy. Encryption has been widely used by several mechanisms in order to send their messages without the risk of being understood by the hackers. Encrypting messages does not allow the hackers to have access to the messages and eliminates the risk of data manipulation. Hence, cryptographic methods play a crucial role in the security of IoT systems. Well-known cryptographic mechanisms include Public Key Infrastructure (PKI), Advanced Encryption Standard (AES), Data Encryption Standard (DES), and Elliptic Curve Cryptography (ECC) rely on cryptographic keys [46, 143]. In PKI-based systems, there are two sets of keys for each user, private and public keys. The private keys need to be kept secret while the public keys can be known by everyone. If one key is used to encrypt a message, the other key needs to be used in order to decrypt the message. These secret (private) cryptographic keys are expected to be robust, reliable and reproducible and they are usually stored in the Non-Volatile Memory (NVM) of the devices. However, the NVMs are highly susceptible to physical attacks.

The cryptographic keys are sensitive information and therefore, several mechanisms have been developed to protect these keys. White Box Cryptography (WBC) is a software based solution to protect these keys and allow secure distribution of valuable information [76]. WBC requires high processing power and memory and is only applicable to symmetric cryptographic methods; therefore, it will not be a competing candidate for the security of IoT networks.
addition, RSA encryption keys are stored on a specialized chip called trusted platform modules, introduced in [82], on an endpoint device (client device) to allow secured encryption. Physical computing devices called Hardware Security Modules (HSM) were designed to safeguard and manage digital keys. HSM requires programming equipment and interfaces to allow fast data transfer. Since the number of IoT devices is increasing rapidly, key management including key generation, key distribution and key storage in large-scale IoT networks is a major challenge in security of IoTs.

In general, there are two types of software-based, and hardware-based mechanisms to protect IoT devices from various attacks. Software-based security mechanisms rely solely on software to protect their messages. As they are based on algorithms, it may be easier to decode the algorithm to extract the secret keys. Therefore, these security mechanisms are vulnerable to many attacks such as malware, phishing, DoS, etc. In software-based security mechanisms, the keys are stored in the NVM of the devices which are prone to attacks. Though software-based security systems were effective all these years, the advancement in hardware and computers may allow the hackers to break the systems such as using quantum computers. Hardware-based security uses a dedicated hardware integrated circuit or processor to perform cryptographic functions and store the keys. They can prevent read-and-write access to data and offer a stronger protection against various attacks. However, hardware-based security is prone to man-in-the-middle attacks. The hardware-based mechanisms such as HSM have been used for crypto processing and strong authentication where it can encrypt, decrypt, store, and manage digital keys. HSM has been used alongside software mechanisms such as PKI, AES to encrypt their messages [14].
Physically unclonable functions (PUFs) are a hardware-based security primitive introduced in 2002 [56]. The PUF utilizes the intrinsic manufacturing variations in a device to generate a fingerprint of the hardware that offers the valuable advantage of unclonability. This means that the device cannot be cloned even when a hacker has physical access to the device. Therefore, the PUFs are unique to their device and can be used as a security primitive to enable device-based identification, authentication, and secret key generation.

PUFs can provide a low cost alternative solution for on-demand generation of cryptographic keys from the device rather than the conventional methods, where the secret keys are produced and distributed by the server and stored in the IoT device memories [37].

The data derived from PUFs is often highly sensitive to environmental changes and the physical conditions where the device is being tested. In other words, the readings from the PUFs are not perfectly reproducible. Therefore, different types of PUFs have been used for the purpose of identification and authentication of devices, where a certain margin of error rate is tolerable. However, even a small amount of variation in the PUF’s responses in different conditions can prevent them from being utilized in key generation because the key used for encryption needs to be perfectly reproducible to decrypt the messages.

1.1 Review of Recent Relevant Survey Papers and the Contributions of this Paper

This survey aims to focus on the applicability of PUFs-based hardware security for key generation and authentication of IoT devices. The paper offers a unique and timely survey compared to existing survey papers in the literature by investigating the role of PUFs in IoT security, in particular providing an additional level of security to common key-based cryptographic methods to generate the keys from the devices. In 2018, authors of [28] discuss the standards of wireless communication in Cyber Physical Systems (CPS) and IoT and focus on security of these systems. The paper does not study the physical side channel attacks in implementation of security mechanisms for these systems. The paper explains in detail, the various wireless communication standards and protocols. Later, it briefly reviews the security threats in IoT and CPS domains and concludes the paper with recommendations on careful selection of devices from sensors to routers, and auditing the systems using dedicated third party surveillance technologies. The paper does not address the problems in identifying malicious nodes and authenticating known users in the network. In [178], several recent challenges are identified as a result of the introduction of IoT and CPS systems are discussed. This work focuses on different attacks and threats for these systems as well as challenges related to implementation of CPS and IoT in the wireless network.

In [97], the security and privacy challenges of IoT in general and possible attacks in different layers of IoT devices were discussed. In particular, this paper discusses the security challenges of fog/edge computing-based IoT. In [11], the use of information-centric networking (ICN) as a possible protocol for addressing IoT devices was introduced. This paper stresses on the need for larger and permanent naming scheme and addressing space for IoT contents and devices. ICN-based solutions for IoTs were discussed along with classification of ICN-IoT architecture into naming, caching, security and mobility fields for applicability of ICN for IoTs. The authors also provided a detailed survey on ICN based caching, naming, security, and mobility approaches for IoTs. In [59], the authors identify different protocols and mechanisms to secure communications in IoT and the security weaknesses of IoT at different layers of communication. In [40], the authors discussed the use of programmable hardware such as FPGAs in network infrastructure security. This paper highlighted the role of hardware-based mechanisms to address some of the challenges in software-based methods, as well as the potential challenges due to the rising demands of intensive analysis and real time operation for sequential processing.
The key contribution of this survey compared to the previously published surveys in the area of IoT security is studying the role of memory-based PUFs in authentication and identification of the various IoT devices. More importantly, we discuss the potential advantages and challenges of using PUF-based secret key generation mechanisms to add another level of security to popular key-based cryptographic methods. Such mechanisms, if successful can enhance the security of a huge number of IoT devices against physical attacks. To the best of our knowledge, the current memory-based PUF techniques do not have the required robustness and reliability to generate fully reproducible secret keys as required in cryptographic systems. This need calls for new PUF generation technologies and robust mechanisms for key generation as discussed in this paper.

This survey paper is organized as follows. In Section 2.1, various security challenges in different domains of IoT networks are presented, with a focus on the applications, architecture, communications, and data domains. In Sections 2.2 and 2.3, different attacks in an IoT network are briefly described. Section 3 explains the chain of integrated circuit manufacturing and points out hardware attacks based on the vulnerable points. Section 5 reviews the PUFs which are based on static random access memories. In Section 4, the concept of PUF, their classification along with their application in different security applications are discussed. In Section 6, ReRAM-based PUFs are explained in details and the challenges in using them for key generation is discussed. In Section 7, the use of fuzzy extractors to generate keys from noisy data is described. In 8, we provide a survey on the state-of-the-art key generation mechanisms. In Section 9, the concluding remarks and future directions of research are discussed.

### 1.2 Abbreviation Table

All of the abbreviations used throughout this paper are summarized in Table 2.

| Abbreviation | Paraphrase | Abbreviation | Paraphrase |
|--------------|------------|--------------|------------|
| AES          | Advanced Encryption Systems | CPS          | Cyber Physical Systems |
| CRP          | Challenge Response Pair      | DoS          | Denial of Service     |
| DDoS         | Distributed DoS              | DES          | Data Encryption System|
| DHT          | Distributed Hash Tag         | ECC          | Elliptic Curve Cryptography|
| HSM          | Hardware Security Modules    | IC           | Integrated Circuit    |
| ICN          | Information Centric Network  | IoT          | Internet of Things    |
| IP           | Intellectual Property        | LDPC         | Low Density parity Check |
| MRAM         | Magnetoresistive Random Access Memory | MQTT | Message Queuing Telemetry Transport |
| NVM          | Non-Volatile Memory          | OSI          | Open System Interconnection |
| OSN          | Online Social Network        | PKI          | Public Key Infrastructure |
| PUF          | Physically Uncloneable Function | RE-RAM | Resitve Random Access Memory |
| RF           | Radio Frequency              | RFID         | Radio Frequency Identification |
| RSA          | Rivest Shamir Aldeman        | SDA          | Software Defined Network |
| SEA          | Secure and Efficient Architecture | SEM | Scanning Electron Microscope |
| SMB          | Server Message Block         | SoC          | System on Chip        |
| SOA          | Secure-Oriented Architecture | SS           | Secure Sketch         |
| SSL          | Secure Socket Layer          | TCP          | Transmission Control Protocol |
| TSL          | Transport Layer Security     | ULP          | Ultra Low Power       |
| UUID         | Universally Unique Identifier | WBC         | White Box Cryptography |

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2 SECURITY CHALLENGES AND ATTACKS IN IOTs

2.1 Security Taxonomy

In this paper, we focus on the security challenges of IoTs and the potential impact of PUF technology to address some of these challenges. In IoT networks, a large number of sensors and devices are connected to the Internet which forms a huge network with mobility and heterogeneity characteristics that entangles protecting the network from security attacks. Moreover, the limited energy and computation capability of IoT nodes restrict the utilization of some conventional security mechanisms in these networks [5, 108]. One key challenge related to utilizing some traditional security protocols is the heterogeneous nature of IoT networks due to the wide variety of applications of these networks. As a result, different applications require different protection mechanisms. In most scenarios, these applications can be categorized by different characteristics such as user association, openness, and heterogeneity. The heterogeneity of IoTs can degrade the efficiency of cryptographic methods that rely on the key generation and key exchange [190]. Furthermore, noting the characteristics of IoT networks, the security attacks such as DoS, routing attack, replay attack, man-in-the-middle, side channel attack, node capture, and mass node authentication are common threats in these networks.

Figure 3 shows the various security concepts for IoT based on four domains namely, application, architecture, communication, and data. Based on these stack layers, a security taxonomy can be defined in IoT. Next, different concepts of security for each of the application, data, communication, and architecture domains are introduced. Then, different sub-domains as authentication, authorization, trust establishment, and exhaustion of resource are explained for the application.

2.1.1 Data. One of the important aspects of security in IoT networks is data privacy and confidentiality which remain critical concerns [25]. In general, confidentiality is a security concept which ensures that unauthorized users cannot
access the data or even try to hijack the information. One of the challenges in IoT networks is dealing with a large number of diverse users and applications, hence it is hard to keep confidentiality. Secure key management is one of the methods which can improve the confidentiality in IoT networks [34, 97]. On the other hand, privacy makes sure that data and information are only accessible by authorized users and cannot be changed by others. Most of the time, the main focus of confidentiality is on the encryption of the data; however, privacy defines the level of access on the received data for different users [97, 188]. Finally, trust is a concept for the user to accept the security, privacy, and confidentiality in each network. Trust imposes privacy, confidentiality, and security among different layers of IoT, or between different devices and applications [9, 50, 97].

2.1.2 Communication. Communication in IoT network is defined based on exchanging or sharing of information and data between the users, devices or even exchanging information between different IoT layers. Noting the wide applications of IoT devices in different domains, several communication protocols have been used in IoT networks leading these networks being vulnerable to various communication attacks [66]. As a result, the communication medium is a bottleneck for many attacks such as Man-in-the-Middle (MitM)[64] and eavesdropping attacks[121].

2.1.3 Architecture. There is no global and specific architectures for IoT networks to validate the security concepts for authorization and authentication. However, various architectures such as Software-Defined Network (SDN) [168], secure and efficient architecture (SEA) [109], smart city [57], service-oriented architecture (SOA), object security architecture (OSCAR) [174], and black SDN [35] are proposed to examine both authentication and authorization.

2.1.4 Application. Scope, scale, heterogeneous, accessible, and repeatable are the application features that can be used to evaluate different security techniques such as authentication, authorization, exhaustion, and trust establishment [62]. Since there is no definite architecture for IoT devices, various techniques have been developed for authentication and authorization in this domain [39]. Noting the wide range of applications of IoT, attacks on these systems can impact several critical domains. Next, different IoT security challenges based on the application domains are introduced.

I) Authentication: The authentication refers to the process of verifying the identity of devices to grant them with information access. Data integrity and unauthorized access to the IoT networks such as impersonating attacks are critical issues in these systems. The objective of the authentication process is to assure that the nodes only carry validated information from the legitimated sources. In order to manage numerous IoT networks offered by different vendors, the IoT devices need to be authenticated to validate their identities before routing any information. The authentication mechanisms usually rely on a certification authority (CA) that involves a fairly heavy load of message exchange between the CA and the low power IoT nodes. The authors of [62] proposed an authentication scheme based on hashing and element extraction used for application layer in IoT nodes. An access control method is implemented in [116] that adopts an ECC-based key establishment. For access control policy, the authors utilized a role-based access control (RBAC) authentication method employing the nodes’ particular role(s) and applications in the corresponding IoT network. One drawback of this work is that it incurs a large number of overhead messages during the access control and authentication mechanisms. In [182], a new authentication method is developed which considers the IoT perception layer. This method enhances mutual authentication between the user and the sensor nodes, and intermediate processes.

II) Authorization: Authorization is defined as how IoT nodes (e.g., sensors or actuators) can access the resource of information. Let us consider an example of IoT application in health care. In this case, the sensitive information such as the critical health profile of the patients are momentous and only authorized nodes or users should be able to access this data. Therefore, the IoT devices should not be able to reveal the data to other unauthorized users or nearby users [1].
III) Exhaustion of resources: The rate of energy consumption of IoT devices varies based on the applications [23]. Resource-exhaustion attacks are another common threat in IoT networks that causes a high rate of resource consumption, and, in particular, energy consumption. For instance, the routing protocols in IoT networks are susceptible to exhaustion attacks, because the existence of loops in routing mechanisms can drain the energy of nodes. In these attacks, the attacker utilizes DoS to target in-range nodes. Since, each receiver responds to the attacker, the depletion rate of resource in each battery increases [26].

IV) Trust establishment: Trust can be defined in three different concepts for IoT networks. i) Trust for security at each separate layer: reliability, confidentiality, and integrity of data should be protected with security and privacy concepts in each layer; ii) Trust between layers: different layers in the IoT networks should protect the privacy and trust during communications; iii) Establishing the trust between the end user and the IoT network: since data is transmitted between the end user and the IoT system, a trust concept should be provided for both ends. In addition, actions of both ends affect the operation for the other side. Therefore, it is crucial to define a robust trust mechanism between the user and the IoT system.

In summary, in the aforementioned key-based security mechanisms, each node in IoT networks needs to locally store the digital secret key for authentication or encryption purposes. Traditionally, most digital keys are stored in non-volatile memories such as ROM or one-time electronic fuse. Nevertheless, using a scanning electron microscope (SEM), attackers can implement many invading threats on these chips. However, using these kinds of memories requires additional fabrication steps during the production of the device. Antifuse or electronic fuse is another security technique which is being used for key storage using FinFET transistors [43]. The main benefit of this technology is that the information is not disclosed from the power consumption during the reading process. Moreover, this technology enhances the reliability of the read procedure. The only disadvantage is that it fails to remove the key from the device. Once the key is exposed, it cannot be eliminated from the chip.

Physical Unclonable Function (PUF) is a principle that is being used for authentication and authorization which does not need any non-volatile memory [56, 132]. They can be also used for cryptographic key generation, where the digital keys are not stored in the device, rather, they are extracted from the physical features of the device. PUFs exploit the random disorder of the physical system in the environment or from the manufacturer. These disorders cannot be re-fabricated again. Hence, they are called intrinsic behavior of the device. Although these features are disadvantageous from the perspective of integrated circuits, they can be advantageous from a security perspective. In recent years, PUFs face many critical challenges such as reproducibility, wireless transmission of data, and exposure to the predictive models for attacks.

In general, cryptographic methods are currently the most reliable way to secure IoT devices in a vulnerable environment. However, power utilization and key storage are amongst the main concerns when implementing these cryptographic methods in IoT networks. Next, we discuss the contributions of PUF technology to IoT security and in particular key generation for cryptographic methods.

2.2 Attacks

The specific characteristics of IoT devices such as low price, low power, and low computational capability as well as the heterogeneity and large-scale of the network limit the applications of common security mechanisms. Therefore, IoTs are prone to several advanced attacks and security issues [94, 115, 165] that calls for novel security mechanisms in different domains, including identification/authentication, reliability, confidentiality, and non-renunciation. In this
section, we review some common attacks on IoTs such as spoofing, altering, replay routing attack, DoS, node capture attack, and Sybil attack.

2.2.1 **Denial of Service Attack (DoS).** In this attack, the attacker tries to exploit all the resources in the network which can seriously degrade the network performance. The DoS attack is also called a computational resource attack. These attacks are categorized into two groups: individual (single) DoS and Distributed DoS (DDoS) [7, 16]. In a single DoS attack, the intruder as a single entity tries to exhaust the resources of the target entity. However, in a DDoS attack, multiple attackers exploit the single entity or a single attacker compromises multiple users to flood the target machine with lots of requests.

2.2.2 **Sybil attack.** Networks with a large number of users are more prone to Sybil attacks. In this attack, a single node is identified with different IDs. This means that the unification of entities will be eliminated from the network [160]. Based on [187], in 2012, 76 million users on Facebook and 20 million users on Twitter were fake. Online Social Networks (OSNs) such as Facebook, Instagram, or Tweet are prone to this kind of attack as they have lots of users. One of the purposes of the Sybil attack is to hijack the information from the OSNs and websites. Since the number of IoT devices is growing rapidly, they are also vulnerable to Sybil attacks. A Sybil attack can cause users to produce fake and false reports. Users might also receive spam messages from fake profiles and fail to keep their privacy. Sybil attacks can be categorized into three different types: SA-1, SA-2, and SA-3 [187]. Different mechanisms including Friend Relationship-based Sybil Detection (FRSD), cryptography-based mobile sybil detection, and feature-based mobile sybil detection are being used to defend IoT networks against Sybil attacks [187].

2.2.3 **Spoofed, Alter, or Replay Routing Information.** In these types of attacks, an attacker changes the routing information or tried to manipulate the routing packets by listening to the legitimate transmitter and impersonate the identity of the real transmitter. Then, it sends fake data to the receiver and introduce loops into the network [160, 184].

2.2.4 **Attacks based on Access-Level.** Based on the level of access to the network, these types of attacks are categorized into two groups namely, passive and active attacks.  
**Passive Attacks:** In most passive attacks, the attacker just eavesdrops the communication between the legitimate transmitter and its receiver to exploit their data. [6, 16, 72].  
**Active Attacks:** In active attacks, the intruder attempts to disturb the connection between the legitimate entities, perform impersonation itself, or even disrupt the connection by manipulating the routing information [16, 72, 107, 135].

2.2.5 **Attacks in Communication Protocols.** The communication functions of IoT networks are commonly described by the TCP/IP model. Table 3 presents the taxonomy of attacks that are possible on the TCP/IP protocol stack.

Figure 4 demonstrates a schematic representation of IoT attacks, some of which have been described in previous subsections. A detailed description of all of these attacks is beyond the scope of this paper. The glowed-arrows and dashed-circles show the concentration path for PUF application in IoT which is the main focus of this paper [15, 29, 55, 72, 111, 119, 124, 141, 148, 179, 187].

2.2.6 **Attacks based on device property.** IoT devices are categorized into two groups: low-end and high-end device class. Based on these types, attacks might have different effects on the devices. They might just result in abnormal behavior or they might stop the devices from working [72].

**High-end device class attacks:** In this class of attacks, powerful devices such as laptops and computers are used to launch attacks on the IoT network. Most of the time, the Internet protocol is used between the attacker and the IoT device.
Table 3. Taxonomy of attacks based on different layers of the TCP/IP reference model

| Layer          | Attacks                                      | Attackers’ Strategies                                           |
|----------------|----------------------------------------------|-----------------------------------------------------------------|
| **Physical**   |                                              |                                                                 |
|                | Jamming [93, 111, 112]                       | With radio interference                                         |
|                | Tampering [15, 92]                           | Making fake nodes                                               |
| **Data Link**  |                                              |                                                                 |
|                | Collision [21, 138, 141]                     | Transmit data at the same time in the same frequency channel    |
|                | Exhaustion [68, 72, 161]                     | Multiple collisions and continuous re-transmission until the node runs out of resource |
|                | Unfairness [29, 171]                        | Repeatedly ask for the channel to limit others’ request         |
| **Network**    | Spooled, or Replayed routing information [27, 72, 98] | Routing loops, changing the source of the route, Repelling network from selected nodes |
|                | Selective forwarding [30, 78, 81]            | Send selected information to the legitimate receiver             |
|                | SinkHole [42, 55, 87]                       | Become the target of all nodes in order to gather all information |
|                | Sybil [24, 121, 187]                        | Create lots of pseudonymous identities to undermine the authorized system |
|                | WormHoles [74, 177]                         | Re-transmit information to the IoT nodes                        |
|                | Hello flood [63, 148, 151]                  | Use Hello messages to flood the network with these tiny messages |
|                | Acknowledgement spoofing [142]              | Spoof the link layer acknowledgement                            |
| **Transport**  | SYN flooding [49, 179, 183]                 | Resend request multiple times to fill the capacity of the transport layer |
|                | De-synchronisation, [75, 119, 127]          | Reinitialize the connection in order to disrupt it               |
| **Application**| Reliability attacks: Clock skewing, Selective message forwarding, Data aggregation distortion [10, 78, 106, 113, 124, 131, 186] | Impersonate itself as a reliable node in the IoT network and sends corrupted data |

In these types of attacks, the intruders can use the computing power of CPUs and even GPUs to launch attacks on the IoT network [12, 100].

**Low-end device class attacks:** In contrast to the previous class of attacks, in this class, the devices which have low power and energy are engaged in attacks on IoT devices. The attacker uses the radio connection between itself and the IoT device to perform the attack. As an example, smart watches or smart home gadgets are very common in every home. These tiny devices connect to your smart home network which includes TV, refrigerator, cooling system, home security and they can control the configurations of these features. However, these smart home utilities could also be attacked by these little IoT devices [13, 96].

2.2.7 *Attacks based on transmitting information.* The purpose of most IoT networks is to sense and collect information from the surrounding environment. For this reason, thousands of sensors are being used to gather information. These
sensors are also vulnerable to various types of attacks which can be used to launch network attacks which can be categorized into six groups:

**Man-in-the-middle attacks:** In these attacks, the attacker is between the legitimate transmitter and the receiver. The attacker relays information between these two entities but may retain valuable information. Figure 5 demonstrates this attack between two parties Alice and Bob. In this example, Alice wants to communicate with Bob. Alice sends a packet to Bob. However, Eve receives the packet and stores the important information and then forwards the packet to Bob. Here Alice and Bob are not aware of the existence of Eve on the network. They think that they have a direct connection to each other [6, 16].

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Message Replay attacks: In this attack, the intruder eavesdrops the channel captures the message and then re-transmits it to the target. Later, after the session is over, they send modified packets to the IoT network to compromise the targeted IoT networks [24, 114].

Fabrication attacks: Fabrication attacks include flooding the IoT network by sending wrong authentication messages to the core of the network. This attack compromises the information being exchanged among the IoT devices [100].

Alteration attacks: In alteration attacks, the intruders try to compromise the communication protocol among the users in the IoT network. They manipulate and alter the information exchange among the users to disrupt the normal operation of the protocols [121].

Eavesdropping attacks: In these attacks, the attackers just intercept the communication between the legitimate transmitter and the receiver to gather valuable information of both users and the network. In this case, the channel and the network are not secure anymore. Hence, the confidentiality among the users in the IoT network may be breached if appropriate mechanisms are not used to protect the information exchanged [88].

Interruption attacks: In this attack, the attackers disrupt the availability of the connection among the users in an IoT network. In this case, the users try to establish the connection and they consume lots of power for the connection. Energy exhaustion is the direct result of this attack [5].

2.2.8 Host-Based Attacks. In this attack, the intruder targets the host resources such as the Operating System (OS) or the hardware. The assumption in this attack is that the intruder has managed to access to the host. Host-based attacks are categorized into three groups: hardware-, software- and user-based attacks. The IoT nodes are usually tiny devices with some applications or software embedded in the OS. The attackers target these three resources of IoT devices and compromise each group with different impact on the overall network [48].

Targeting the hardware: In hardware-based attacks, the attackers manipulate the hardware or try to compromise the driver applications of the targeted hardware. Sometimes they insert malicious code on the micro-controller to attack the driver. In other cases, the attackers replace the hardware and place the destructive one instead of the legitimate hardware [20].

Targeting the software: In this attack, the intruders exploit the resources (such as power, battery or even buffer and queues of the different applications or protocols) of the users in an IoT network. Hence, battery depletion, buffer overflow, or a full queue (stack) might be the results of this attack [189].

Targeting the user: This attack steals valuable information such as secret keys, passwords, hash tables, or protocol rules from the user. Storing this information in users’ memory attracts attackers and intruders to the host [18, 65].

2.3 Classification of IoT Security Attacks

In section 2.1, we reviewed security challenges in IoT networks and we presented a security taxonomy. Then, Section 2.2 summarized common attacks based on TCP/IP stack layers. In this section, we classify common attacks based on the IoT ecosystem. Although there is no well-defined layered model for IoT; Figure 6 illustrates a three-layered model for
IoT devices [155]. These layers include perception, network, and application. First, we describe each layer and then we present a classification of attacks with respect to the different layers in Table 4.

2.3.1 Perception layer. The lower layer of the IoT network, the perception layer, is responsible for the interconnection of the nodes in the network. For instance, Arduino boards can use the Ethernet to get access to the Internet, Raspberry Pi can use the Ethernet, WiFi module, or the Bluetooth module to connect to the Internet or other nodes. Each of the communicating devices should have a unique identification called the Universally Unique IDentification (UUID) [91]. Most of the time, these IDs are interchangeable. Hence, they are embedded in the hardware as System-on-Chip (SoC) or are provided by a secondary chip [156].

2.3.2 Network layer. This layer includes interfaces, communication channels, network management, addressing, and so on. It is also responsible for all communications and connectivity for all devices in the network using multiple communication protocols [180]. Unlike the Internet, there is no standard protocol for the network layer for IoT devices. However, Message Queuing Telemetry Transport (MQTT) 3.1 [73] and Constrained Application Protocol (CoAP) [149] are two common protocols for the IoT networks. This layer transmits information within the network (other nodes) or outside of the network (e.g., the Internet or a sensor network). Since devices in an IoT network have a limited amount of energy and computation, the role of addressing, forwarding, and routing is pivotal in such networks.

2.3.3 Application layer. This layer makes sure that different entities in the network communicate using the same type of service. This layer is also called the service-oriented layer [80] and it handles data for different applications based on...
user requirements and demands. For instance, for applications such as smart transportation, smart home, and eHealth, it can store data into an appropriate database [80].

2.3.4 Classification of attacks in IoT networks. IoT is utilizing various available network backbones such as wireless sensor networks, the Internet, RFID, and so on. Hence, it is crucial to categorize all attacks based on the layers of IoT we have identified in this section. Table 4 provides an overview of some of these attacks. Since certain tiny IoT devices are not able to implement some encryption methods, PUF may come handy to enhance the security of these devices.

Table 4. Taxonomy of attacks with respect to the different layers in the IoT structure

| Encryption attack | Perception attacks | Network attacks | Application attacks |
|-------------------|--------------------|-----------------|--------------------|
| Side Channel attack | Node tampering | Sybil attack | Virus and worms |
| RF interference | Route information attack | Spyware and adware |
| Man-in-the-middle attack | Node jamming | Sinkhole attack | Trojan horse |
| Malicious node injection | RFID spoofing | Denial of service |
| Physical damage | RFID cloning | |
| Crypto attacks | Social engineering | Man in the middle attack | Malicious script |
| Sleep deprivation attack | Denial of service | |

3 HARDWARE-BASED SECURITY

In the previous section, we reviewed software-based security challenges and attacks. However, based on the production line for Integrated Circuits (ICs), there are several vulnerabilities based on hardware designs. Figure 7 shows this semiconductor manufacturing process chain which consists of different tasks. As a result of the fast and growing trends in IC manufacturing and production, this global supply chain can be targeted and attacked at different vulnerable points. Some common threats faced by the manufacturing process include fake copy, side-channel attack, reverse engineering, Intellectual Property (IP) hijacking, and hardware Trojans. Next, we review hardware-based attacks and threats disucced in [128, 129].

3.1 Fake Replica

In this attack, the intruder counterfeits the original IP illegally. Fake replica and piracy are totally different. Piracy means overbuilding the entire IC. This might happen because the attacker gets access to the design information at different points such as the design or the fabrication. However, a fake replica might happen at different stages such as recycling, packaging, or the new vendor [86]. Fake replica or counterfeiting can be very harmful to the industry. Since the attacker uses the reputation of the original designer, instead he/she uses expired or old designs to rebuild the ICs or IPs. In most cases, the attacker wants to earn more money by selling fake products. However, he/she can also put malicious circuits such as Trojans into those ICs and compromise different critical products and applications such as airplanes, vehicles, drones and UAVs, elevators, and so on.
3.2 Side-Channel Attack

In some cases, physical states’ parameters such as power consumption, timing values, or electromagnetic reflection from hardware can reveal important information to the intruder. In most cases, such information sets can be extracted when the application is being executed where the attacker can perform different tests. Such attacks which involve extracting the behavior of devices [126], are very common in public-crypto systems such as Rivest-Shamir-Adleman (RSA). RSA uses public and private keys which encrypts and decrypts messages based on modular operations and large exponential values. Two common approaches include calculating the multiplication chain: the first one uses the naive multiplication operation and the second one uses square-and-multiply method [44, 103]. In both scenarios, the attacker can use delay analysis to perform a timing side-channel attack. Delay analysis measures the execution time for a number of multiplications which the system uses to calculate the exponential results [176]. In addition to timing side-channel attacks, other attacks such as measuring the photonic emissions, systemic acoustic noise, power consumption, and electromagnetic emissions are common in crypto systems [58, 125, 140].

3.3 Reverse Engineering (RE)

Reverse engineering is the process wherein the intruder follows a reverse path from the application to the design point for the IC or the IP to reconstruct it, modify it, or implant malicious circuit into it. RE may involve different steps such as i) detecting the technology model which is being used in the design and fabrication steps [19], ii) taking out different parts of design such as gate, logic, circuit, and physical [164], and iii) discovering and observing the functionality of the IP or the IC [128, 136]. RE might have different objectives such as hijacking the design, illegally replicating the IC and announcing the technology used in the design. The intruder might use a table of information based on a defined pair of inputs and outputs to evaluate the behavior of the circuit. In this way, the attacker can verify the gate level design from the IP/IC. The goal of the attacker might be hijacking at the gate-level, circuit-level, or physical design by performing
reverse engineering in order to extract an abstract level of the IP. The attacker can use the abstract level to reproduce the product and to sell it illegally or implant a malicious circuit into the product.

### 3.4 Intellectual Property (IP) Hijacking

When the IC is designed, the designers of the IP company or people involved in the fabrication process might hijack the design information without respecting the copy-right terms. Moreover, an attacker at the fabrication stage may reproduce additional chips to sell them on the black market. In these cases, unreliable people can steal the design information and claim the ownership of the IP or the IC [130]. For instance, they are three IP piracy methods. In one case, the attacker can steal the third-party’s IP. In another case, the intruder can steal the layout design. Finally, the intruder may take the IC design in the fabrication process and try to rebuild many others.

### 3.5 Trojans in Hardware

Malicious modifications to an IC can be defined as a hardware Trojan. This Trojan can mislead the communication or cause a failure in control and processing units. In this kind of attack, the intruder can modify and alter the circuit or add a malicious circuit to it. Since the testing procedures are usually slow and expensive, it is hard to detect the hardware Trojans after wafer fabrications. Moreover, the technology is merging with Nano- and Pico-meter fabrication design and because of the large space inside of ICs, there are many locations for implanting Trojans. Such locations include different design points such as logic, circuit, and physical and the fabrication process [79, 163, 175].

After introducing hardware-based attacks, Figure 8 summarizes these attacks and indicates which entities are vulnerable to specific attacks in the semiconductor manufacturing chain. Section 4 introduces the concept of PUFs and their roles to prevent the aforementioned attacks.

### 4 PHYSICALLY UNCLONABLE FUNCTIONS (PUFS)

Physically Unclonable Functions use the unique variations introduced in the fabrication of the device, to extract a fingerprint unique to the device. One or more specific parameters of the device such as threshold voltage, critical dimensions etc., are measured when an external stimulus is applied. When the devices’ parameter is being measured for the first time, the measurement is called a challenge and is stored in the server. When the same parameter is measured again when the same external stimulus is applied it is called a response. The challenge and response form a pair, called the Challenge Response Pair (CRP) and are generally compared with each other to verify the authenticity of the device.

The difference between the challenge and response of a PUF is referred to as the challenge response error.

PUFs can be generally classified into two broad categories: “strong PUFs” and “weak PUFs” based on the number of possible CRPs. Weak PUFs leverage the manufacturing variability and allow digitization of some “fingerprint” of the hardware device. The number of responses in a weak PUF is directly proportional to the number of components in the device used for generation of CRPs [79]. This fact results in a small number of CRPs with stable responses which are usually robust to environmental conditions. Weak PUFs are generally used for secret key generation because the responses are more stable and hence easily reproducible. Strong PUFs can support a large number of CRPs. Ideally, if the number of unique CRPs is high, even though an attacker gets temporary accesses to the system, he/she will not be able to apply all the responses (brute force attack) and get access to the system. Hence, strong PUFs are generally used for authentication[70]. However, a large set of PUF responses may offer stronger cryptographic strength as it leads to longer cryptographic keys [104]. The entropy of a PUF is defined as the total number of independent CRP’s that can be produced from a PUF and is directly proportional to the number of bits that can be extracted from it. Independent CRP
refers to the fact that if one CRP is known, one cannot predict the other CRPs in the PUF, hence there is no shared information between two CRPs.

Usability of PUF can be determined by two statistical parameters of intra-distance and inter-distance which are defined as follows:

- Intra-distance: the Hamming or the fractional Hamming distance between two different responses to the same PUF challenge
- Inter-distance: the Hamming or the fractional hamming distance between two responses of two different PUFs to a given challenge.

For a given PUF, these measurements hold the values of reproducibility and uniqueness, respectively.

During the registration process, the server first sends the client a query which is usually the external stimulus to which we would like to record the behaviour of the device, thereby extracting a challenge from the device, which is usually a string of bits that will be stored in the server. These challenges will be stored in a secured memory of a server to allow authorization of the device when appropriate. During authentication, the server sends the same query to the PUF and its behavior to the stimulus is sent to the server as "response" which is compared against the "challenge" stored in the secure memory. PUF-based security mechanisms rely on building unique CRP's. The two primary applications of a PUF include low cost authentication and secret key generation. During authentication, the PUFs are queried by challenges and authentication is granted only if the rate of matching responses is statistically high enough [31]. The amount of error between the challenge and the response is called Challenge Response Pair (CRP)
error. Another application of PUFs is to utilize the high randomness introduced during its manufacturing to create a secure key from the device. Such key generation requires ideal PUFs that are robust, tamper evident, and unpredictable. Using a secure sketch in a fuzzy extractor which we explain in the following sections, we are able to correct noise from a physical PUF and use it for key generation schemes. Secure sketches use the concept of error correction coding to ensure that we recover the original PUF data from the noisy PUF.

4.1 Types of PUFs

Different types of PUFs can be made by making use of different components of the device to extract a fingerprint. Initially randomness was physically introduced into a device to extract a fingerprint such as optical and coating PUFs. An optical PUF consists of a transparent material which contains scattering of light particles in an uncontrolled manner. When a laser beam falls on it, a unique and random pattern is produced [118]. A coating PUF can be built by filling the space between a network of metal wires on top of an Integrated Circuit (IC) with an opaque material which is randomly doped with dielectric particles. The capacitance between each set of wires will be a random value because of the random placement of doping, the dielectric’s strength and size. This PUF is generally used on the top layer of the ICs which is generally used to protect the underlying circuits from attackers’ inspection. When a part of the coating is removed, the capacitance of the wires is bound to change. These PUFs have been used as RFID tags [166].

Current technologies prefer to utilize the PUFs designed based on intrinsic variations, because they are already embedded in the device. Silicon PUFs exploit the intrinsic variations in the IC manufacturing process. The first silicon based PUF was introduced in 2002 by Gassend et al. Leaked current-based PUFs whose work was based on the idea that different physical variations of the same circuit will result in a different leakage current. Another example of silicon PUFs are delay-based PUFs, where in even using an identical layout will cause distinct delays due to the manufacturing variations in its components. Arbiter PUFs and Ring Oscillator PUFs are common examples of delay based PUFs [144]. These PUFs need large groups of device components to make them secure. These PUFs tend to take a large amount of chip space and are vulnerable to side channel attacks because they give off information due to heat and therefore, they may not be suitable for IoT nodes.

4.1.1 Memory based PUFs. Memory-based PUFs use the memory already present in chips/devices and hence can be implemented in simple devices with few or no extra parts added, to allow authentication in a network. PUFs can be made from different types of memory including SRAM, Flash, MRAM, memristor, and ReRAM. The memory cells are usually in an unstable state (power up) and should be allowed to settle to a preferred stable state before programming the memory cell to a binary value. Therefore, it may take some time for the cells to supply a binary value as in the case of SRAM, or voltage in ReRAM PUF. These PUFs can be regarded as both strong and weak PUFs. SRAM-based PUFs are often prone to side channel attacks which track the power generated during authentications using a signal analyzer [32]. Since SRAM PUFs use CMOS architecture, they can be easily integrated into a system but they give away side channel information when switching states. This can be detected by checking the laser’s wavelength. As a result, hackers can have enough information to clone the device [69]. PUFs designed using Re-RAMs are attractive compared to Flash because they are faster and can operate at or below noise level which makes them resistant to side channel attacks without direct access to the chip. Re-RAM and Magnetoresistive random-access memory (MRAM) offer low power options when compared to current Flash technologies because they rely on resistance. The operating power of Re-RAM is around 10pJ/bit compared to 1mJ for Flash and 100pJ for MRAM. Table 5 compares the operation requirements for Flash, Re-RAM and MRAM.
Table 5. Operation requirements for current and novel memory technologies[36][4][162]

| Operation                  | Flash                  | ReRAM                  | MRAM                  |
|----------------------------|------------------------|------------------------|-----------------------|
| Program parameter          | NOR Vds = 5V; NAND Vgb = 15V | Vset = +100mV          | Current: 500uA        |
| Program power required     | 1mJ/bit                | 10pJ/bit               | 100pJ/bit             |
| Program speed (ns)         | 5000ns/block           | 2-20ns                 | 2-20ns                |
| Read parameter             | Voltage: 10mV          | Current: 1-20uA        | Current: 1-20uA       |
| Read power required        | 10 pJ                  | 1pJ                    | 1pJ                   |
| Read speed (ns)            | 50ns                   | 2-20ns                 | 2-20ns                |

Table 6. Comparison of different types of PUFs.

| Type       | Name    | Weak/Strong | Ref                  | Comment                                  |
|------------|---------|-------------|----------------------|------------------------------------------|
| Special   | coating | Weak        | [152, 153, 167]      | Smaller number of CRP                     |
| Optical    |         | Strong      | [90, 133, 153]       | Difficult to evaluate the uniqueness     |
| Silicon    |         |             |                      |                                          |
| PUF        | Delay   |             |                      |                                          |
|           | based   | Arbiter     | Strong               | [52, 110, 158]                         | Vulnerable to attacks                     |
|           |         | Ring        | Weak                 | [105, 144, 185]                        | Needs large power and space              |
|           |         | Oscillator  |                      |                                          |                                          |
| Memory     | based   | Re-RAM      | Strong               | [2, 33, 120]                          | Very sensitive to environmental and voltage fluctuations |
|           |         | NOR         | Weak-Strong          | [41, 157]                              | averaging reads increases reliability of PUF response |
|           |         | Butterfly   | Weak                 | [89, 134]                              | unstable adjoining will effect PUF response |
|           |         | SRAM        | Weak                 | [45, 60, 61]                           | Vulnerable to side-channel attacks        |

4.2 Comparison and Applications of Different Types of PUFs

Table 6 demonstrates different PUFs based on their types and their specific features. Since the goal of PUFs is to enhance the security of entities and nodes in a network, they can utilize the physical and application layer to enhance the security. We can also develop a cross-layer design which considers PUF along with these two layers. However, there is no need for any additional implementation, it is possible to use the built-in structures and element to enhance the security for the aforementioned layers (physical and application). Based on the security challenges mentioned in sections 2.2 and 2.3, PUFs are introduced to address several security issues of IoT networks. In most scenarios, PUFs are used to achieve authentication and authorization.

5 STATIC RANDOM ACCESS MEMORY (SRAM) BASED PUFs

SRAM cells consist of cross-coupled inverters connected by access transistors and because of intrinsic manufacturing variations, SRAM cells will typically settle into a “0” or “1” state consistently [22, 173]. SRAM PUFs were introduced in [71] where the initial values of the cells, on powering on the SRAM were used to generate a unique fingerprint. The mismatch between the transistors in a SRAM cell determines the value (“0” or “1”) to be assigned to it. The output of an SRAM PUF is a combination of a various SRAM cells in the memory. The implementation of memory-based PUF is easy and inexpensive because every micro-controller includes a memory which can be used to generate cryptographic keys. SRAMs tend to emit energy when they switch states which can be detected by checking the wavelength of the laser by using a signal analyzer. This side channel information leaked will give the attacker enough information about the
device in order to clone it [32]. These PUFs are most common memory-based PUFs but, they are considered as weak PUFs due their size limitations.

6 RESISTIVE RANDOM ACCESS MEMORY (RE-RAM) TERNARY PUF

Emerging systems use advanced state-of-the-art technology for its memory, which include Re-RAM, memristive devices and Magnetic Random Access Memory (MRAM). Memristor and Re-RAM rely on resistive technology to store information. The manufacturing of Re-RAM is very similar to CMOS technology and hence it can be easily integrated into the IC. Voltage is used to program Re-RAM and erase cells while current is used to read the resistance values of the cells [120]. These devices have high randomness which occurs not only in separate dies but also in the same die. Only specific parameters such as low and high state resistance which are used to represent "0"s and "1"s in making the challenge and response pairs in the device can be measured consistently.

In a conductive Re-RAM, two dissimilar metals with different conductance values are used. When voltage is applied, the filament inside Re-RAM forms a bridge and a hole is left in its place when the voltage is reversed. A metal-oxide Re-RAM works in a similar way but it uses two metal plates separated by an oxide. The oxygen vacancies formed while programming the device will create a high resistance state and the erased cell will have a low resistance because the oxides will be evenly distributed.

Re-RAM PUFs will play a vital role in hardware security in the future due to their high randomness which occurs during the manufacturing process. This high randomness requires for good error correction codes. This device is sensitive to temperature and noise but offers the benefit of being at or below noise level which makes them more secure. The memory cells are affected by aging, operating temperature and operating voltage. Some cells may tend to die faster which can cause a change in the PUF output that may hinder the implementation of the system because it causes problems in the reliability of bits.

Re-RAM based PUFs use the value of $V_{set}$ after programming or the resistance of each cell, to differentiate between "0" and "1" states. The cells close to the threshold can flip one way or the other during response generation when they are subjected to voltage changes, temperature, aging or electromagnetic interference. This could result in 5-20% CRP matching error rate if the number of marginal cells is high. [32] offers a solution to this behavior by identifying three types of cells "0","1" and "X". The cells that are too close to the threshold and are not reliable are blanked by an "X". Figure 9 shows the number of cells whose resistance value are close to the threshold, and therefore can be blanked by an "X".

A solution to store the three elementary states described was provided in [32]. The memories were segmented by pairs of rows or columns and the first column of each pair was named active column and the other companion column. The physical parameter was measured on the active area and the cells that are below the first threshold were characterized as "0"s, cells above second threshold were "1"s and the cells in between were labeled "X"(ternary state). When the active cell of a row is characterized as a solid "0", "0" is programmed in this cell and a "1" is programmed in its companion cell. Similarly, when a cell is characterized as a solid "1", "1" and "0" are programmed in the active cell and companion cell, respectively. Cells without solid bits were programmed with identical bits in active and companion cells, "0,0" and "1,1" [32].

Around 68% of the ReRAM cells were blanked, "X" as their $V_{set}$ was close to the threshold and the rest was used for CRP generation to generate a 128 bit PUF in a memory array of 1000 bit range, where 50% of the cells were used as companion cells. The results showed a CRP error rate of 8 per million. This was expected to improve reliability with low False Negative Authentications and low False Positive Authentications.
6.1 Challenges with PUF Technologies

Analog physical parameters of the fabricated circuit are used to derive the fingerprint of the hardware. These parameters are prone to noise and may change due to temperature, supply voltage and other parameters. The digital fingerprint of the PUF may vary due to changes in any of the parameters mentioned before. Differential design techniques are applied in order to mitigate some of the environmental dependencies in a PUF to make it more stable [70].

Although differential design techniques may improve reliability, the change in environmental conditions will introduce noise in the PUF output. Noise may cause one or more PUF output bits to be flipped resulting in a false negative. Different error correction coding techniques are being employed in order to improve the reliability of the PUF using ‘Fuzzy Extractor’ schemes elaborated in section 7. Various error correcting codes have been utilized to reduce the intra PUF variation factor and improve the similarity of PUF responses for the same query [70]. Adding redundant information (parity bit or helper data) will increase the probability of error detection and correction during the challenge response authentication. Linear block codes and 2-D Hamming codes were used earlier in several PUFs. Taking into account the number of challenges that hinder the perfect reproducibility of the PUF response, we need mechanisms which will reduce the intra hamming distance of the PUF responses.

7 FUZZY EXTRACTORS

A Fuzzy Extractor (FE) extracts a uniformly random string $R$ and non-secret string $P$ (helper data) from its initial input $w$. This mechanism allows the string $R$ to be used as a key and reproduced exactly with the help of $P$, even though the input changes to some $w'$ but remains close to $w$. Fuzzy extractors are said to be information-theoretically secure,
i.e., a crypto-system whose security is derived only from information theory, where a hacker does not have enough information to break the encryption, thereby allowing them to be used in cryptography.

\[ w \in \mathcal{M} \]

![Secure Sketch Diagram](image)

Fig. 10. Secure Sketch

FEs are constructed using Secure Sketch (SS), which is a pair of randomized procedures “sketch” and “recover” that allow precise reconstruction of the initial input from noisy input by making use of some helper data \( P \).

In the “sketch” phase, Helper Data \( P \) is extracted from initial input \( w \), which can be made publicly available. This output \( P \) will be used in the “recover” phase along with noisy input \( w' \) to recover \( w \). This method is secure because the publicly available Helper Data reveals little to no information about \( w \). Figure 10 describes a secure sketch.

\[ w \in \mathcal{M} \]

![Fuzzy Extractor Diagram](image)

Fig. 11. Fuzzy Extractor

FE is defined by a pair of randomized procedures “generate” and “reproduce”. In the “generate” phase, the fuzzy extractor uses the “sketch” phase of the SS where Helper data, \( P \) and Key, \( R \) are extracted from the given input \( w \). The...
"reproduce" phase uses the "recover" phase of the secure sketch which makes use of the Helper data to recover the original input $w$ from a noisy input $w'$ along with the random extractor used in the "sketch" phase, to extract the randomness from the recovered $w$. The ability to recover $w$ from $w'$ is highly dependent on the technique, usually an error correction scheme, used in the "sketch" phase of the FE. If the distance between the noisy input $w'$ and input $w$ is too large, it may not be possible to recover $w$ from $w'$. Figure 12 shows the construction of a FE using a secure sketch. Due to the error tolerance capability of Secure Sketches, their construction is based on error correcting codes. The error correcting code $C$ is used to correct errors in $w'$ by shifting the codeword, although $w'$ may not be in $C$. Two different constructions are used for secure sketch are presented [46]:

- Code-Offset Construction: For input $w$, a uniformly random codeword $c$ is selected from $C$, and $SS(w)$ to be the shift needed to get from $c$ to $w$: $SS(w) = w - c$. To compute $Rec(w', s)$, the shift $s$ is subtracted from $w'$ to get $c' = w' - s$; $c'$ is decoded to retrieve $c$ and $w$ is computed by shifting back to get $w = c + s$. When code $C$ is linear, the information in $s$ is essentially the syndrome of $w$.

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• Syndrome Construction: The sketch $SS(w)$ computes $s = syn(w)$, where $syn$ is the syndrome. To recover the key, a unique vector $e$ is chosen such that $syn(e) = syn(w') - s$ and output $w = w' - e$.

Bose-Chaudhuri-Hocquenghem (BCH) codes which are a part of cyclic error correcting codes, have been implemented in fuzzy extractors, where 192 syndrome bits out of 255 bits were exposed as helper data offered a stability of 88% to a PUF correcting 30 errors in a noisy PUF [159]. High performance error correction coding schemes such as Convolution Coding and Low Density Parity Check (LDPC) are applicable to PUF error correction but are highly complex to implement. It is practical to use good error correction codes which consider maximum likelihood estimation, implementation complexity and secret key leakage to improve the performance of the PUF.

8 GENERATION OF CRYPTOGRAPHIC KEYS FROM PUFS USING FUZZY EXTRACTORS

Secret key generation using PUFs will allow users to produce a key from their own devices which need not be stored in the devices’ memory. Using PUFs to produce keys, will make the device unclonable and hence less susceptible to hacking. Additionally, the use of PUFs eliminates the security issues related to key storage and distribution. Different PUFs have been used in the past to generate reliable and reproducible cryptographic keys using FE.

Different schemes have been proposed in the literature for generating reproducible keys using PUFs [77, 90, 95, 154, 158, 191]. The key generation scheme proposed in [77] uses BCH codes and random number generators for the construction of fuzzy extractors. The main goal of BCH codes is to help reconstruct the PUF estimate from noisy PUF data in order to be used in the "secure sketch" phase of the FE.

This scheme is one of the primitive schemes and does not require any complex decoders. Hence the error correction capability is not good. This scheme may be suitable for authentication where a certain error margin can be tolerated. In key generation schemes, where the key is used for encrypting or decrypting the data, the error in reproducing the key has to be zero.

Many papers in the literature have proposed different FE architectures. Table 7 presents a comparison of the results obtained by these different architectures.

| Fuzzy extractor construction                  | Key length | Helper data bits | Failure probability | Flipping probability |
|----------------------------------------------|------------|------------------|---------------------|----------------------|
| Reed Muller Generalized Multiple Concatenated coding [101] | 128        | 13952            | $10^{-6}$           | 15%                  |
| BCH Repetition Code [102]                    | 128        | 2052             | $10^{-9}$           | 13%                  |
| Generalized Concatenated (GC) Reed Muller[122] | 2048       | 2048             | $5.37 \times 10^{-10}$ | 14%                  |
| GC Reed Solomon[122]                         | 1024       | 1024             | $3.47 \times 10^{-10}$ | 14%                  |
| Polar Codes with SC [38]                     | 128        | 896              | $10^{-6}$           | 15%                  |
| Polar Codes with Hash-Aided SCL decoder [38]  | 128        | 896              | $10^{-9}$           | 15%                  |
| Serially concatenated BCH-Polar Codes with SC decoder [85] | 250        | 262              | $10^{-8}$           | 15%                  |
| Serially concatenated BCH-Polar Codes with Belief Propagation decoder [85] | 250        | 262              | $10^{-10}$          | 15%                  |

In a recent research work proposed in [38], a FE structure based on Polar codes for SRAM PUFs was proposed. This work utilized complex Hash-Aided SC decoder to ensure that the key was reproducible. The results showed that the
key was reproducible with a failure probability of $10^{-9}$ and utilized 896 helper bits for a key of 128 bits. In [84], we used a custom-built Arduino shield to read the fingerprint of SRAM PUF devices. We later compared the efficiency of different fuzzy extractor schemes to generate reliable and reproducible keys while estimating the FAR and FRR. The FE techniques proposed in the literature utilize long Helper data bits and complex decoder structures to extract the low failure probability rates. There is a high probability in increasing the FAR and FRR of the PUF based Keys when using high complex- sophisticated decoders as these were designed to extract the message from very noisy channels, which may not be the best solution to PUF based keys. Further research to understand the average error rate of each PUF and using mechanisms appropriate for the PUF will help mitigate such situations.

9 CONCLUSION AND FUTURE DISCUSSION

This survey paper reviews different security challenges in IoT networks and devices. Different domains such as data, communication, architecture, and application are considered for the security taxonomy in IoTs. Software attacks are discussed based on these aforementioned domains. Then, we reviewed the semiconductor manufacturing process chain which consists of different tasks to accomplish the hardware design for ICs. This chain brings various vulnerabilities in different points which can be considered as hardware attacks. PUFs are considered as one of the potential solutions to counter the hardware based attacks. Noting the challenges of using PUFs due to the variations between different responses. We surveyed various methods to extract keys from noisy PUF responses using fuzzy extractors schemes. The importance and need for using the fuzzy extractors schemes for generating cryptographic keys from PUFs is discussed. A brief discussion on the probability of FE schemes to over correct the Noisy PUF responses and leading to false authentication rate or false rejection rate is discussed.

The future directions of using PUFs need to focus not only on extracting reproducible schemes from Noisy PUFs but also to understand the behaviour of each PUF for different environmental and physical conditions. This challenge required designing schemes that will tailor themselves to the expected error in each device, thereby not allowing under correction or over correction of the PUF responses; thereby reducing the false rejection rate and false authentication rate of the PUF.

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REFERENCES

[1] Mohammed Riyadh Abdmeziem and Djamel Tandjaoui. 2015. An end-to-end secure key management protocol for e-health applications. Computers & Electrical Engineering 44 (2015), 184–197.
[2] Fatemeh Afghah, Bertrand Cambou, Masih Abedini, and Sherali Zeedally. 2018. A ReRAM Physically Unclonable Function (ReRAM PUF)-based Approach to Enhance Authentication Security in Software Defined Wireless Networks. International Journal of Wireless Information Networks (2018), 1–13.
[3] Fatemeh Afghah, Alireza Shamsoshoara, Laurent Njilla, and Charles Kamhoua. 2018. A Reputation-based Stackelberg Game Model to Enhance Secrecy Rate in Spectrum Leasing to Selfish IoT Devices. arXiv preprint arXiv:1802.05832 (2018).
[4] Hiroyuki Akinaga and Hisashi Shima. 2010. Resistive random access memory (ReRAM) based on metal oxides. Proc. IEEE 98, 12 (2010), 2237–2251.
[5] Fadile Ayotunde Alaba, Mazliza Othman, Ibrahim Abaker Targio Hashem, and Faiz Alotaibi. 2017. Internet of Things security: A survey. Journal of Network and Computer Applications 88 (2017), 10–28.
[6] Sahabul Alam and Debashis De. 2014. Analysis of security threats in wireless sensor network. arXiv preprint arXiv:1406.0298 (2014).
[7] Ebrahim Alsaadi and Abdallah Tubaihat. 2015. Internet of things: features, challenges, and vulnerabilities. International Journal of Advanced Computer Science and Information Technology 4, 1 (2015), 1–13.
[8] American College of Cardiology. 2018. Can Your Cardiac Device Be Hacked? https://www.acc.org/about-acc/press-releases/2018/02/20/13/57/can-your-cardiac-device-be-hacked

Manuscript submitted to ACM
A Survey on Hardware-based Security Mechanisms for Internet of Things

[9] Ioannis Andrea, Chrysostomos Chrysostomou, and George Hadjichristofi. 2015. Internet of Things: Security vulnerabilities and challenges. In Computers and Communication (ISC), 2015 IEEE Symposium on. IEEE, 180–187.

[10] Chirsil Arackaparambil, Sergey Bratus, Anna Shubina, and David Kotz. 2010. On the reliability of wireless fingerprinting using clock skews. In Proceedings of the third ACM conference on Wireless network security. ACM, 169–174.

[11] Sobia Arshad, Muhammad Awais Azam, Mukhtar Husain Rehmani, and Jonathan Loo. 2018. Recent advances in information-centric networking based Internet of Things (ICN-IoT). IEEE Internet of Things Journal (2018).

[12] Ahmed W Atamli and Andrew Martin. 2014. Threat-based security analysis for the internet of things. In 2014 International Workshop on Secure Internet of Things. IEEE, 35–43.

[13] Emmanuel Baccelli, Cenk Gündogan, Oliver Hahn, Peter Kietzmann, Martine S Lenders, Hauke Petersen, Kaspar Schleiser, Thomas C Schmidt, and Matthias Wälisch. 2018. RIOT: An open source operating system for low-end embedded devices in the IoT. IEEE Internet of Things Journal 5, 6 (2018), 4428–4440.

[14] Elaine Barker and Allen Roginsky. 2011. Transitions: Recommendation for transitioning the use of cryptographic algorithms and key lengths. NIST Special Publication 800 (2011), 131A.

[15] Alexander Becher, Zinaida Benenson, and Maximilian Dornseif. 2006. Tampering with motes: Real-world physical attacks on wireless sensor networks. In International Conference on Security in Pervasive Computing. Springer, 104–118.

[16] Abhijit Belapurkar, Anirban Chakrabarti, Harigopal Ponnapalli, Niranjan Varadarajan, Srinivas Padmanabhan, and Srikant Sundararajan. 2009. Distributed systems security: issues, processes and solutions. John Wiley & Sons.

[17] Malay Bhayani, Mehul Patel, and Chintan Bhatt. 2016. Internet of Things (IoT): In a way of smart world. In Proceedings of the international congress on information and communication technology. Springer, 343–350.

[18] Suman Sankar Bhunia and Mohan Gurusamy. 2017. Dynamic attack detection and mitigation in IoT using SDN. In 2017 27th International Telecommunications Network Applications and Services Conference (ITNASC). IEEE, 1–6.

[19] Yu Bi. 2016. Enhanced Hardware Security Using Charge-Based Emerging Device Technology. University of Central Florida, Thesis in Ph.D. (2016).

[20] Rajendra Billeure, Varun M Tayur, and V Mahesh. 2015. Internet of Things:a study on the security challenges. In Advance Computing Conference (IACC), 2015 IEEE International. IEEE, 247–252.

[21] Andrey Bogdanov. 2008. Multiple-differential side-channel collision attacks on AES. In International Workshop on Cryptographic Hardware and Embedded Systems. Springer, 30–44.

[22] Christoph Böhmi, Maximilian Hofer, and Wolfgang Pribyl. 2011. A microcontroller sram-puf. In Network and System Security (NSS), 2011 5th International Conference on. IEEE, 269–273.

[23] Eleonora Borgia. 2014. The Internet of Things vision: Key features, applications and open issues. Computer Communications 54 (2014), 1–31.

[24] Tuhin Bogohain, Uday Kumar, and Sugata Sanyal. 2015. Survey of security and privacy issues of internet of things. arXiv preprint arXiv:1501.02211 (2015).

[25] Alessio Botta, Walter De Donato, Valerio Persico, and Antonio Pescapé. 2014. On the integration of cloud computing and internet of things. In 2014 International Conference on Future Internet of Things and Cloud. IEEE, 23–30.

[26] Alessio Botta, Walter De Donato, Valerio Persico, and Antonio Pescapé. 2016. Integration of cloud computing and internet of things: a survey. Future Generation Computer Systems 56 (2016), 684–700.

[27] Martina Brachmann, Sye Loong Keoh, Oscar Garcia Morchon, and Sandeep S Kumar. 2012. End-to-end transport security in the IP-based internet of things. In Computer Communications and Networks (ICCCN), 2012 21st International Conference on. IEEE, 1–5.

[28] Andreas Burg, Anupam Chattopadhyay, and Kwok-Yan Lam. 2018. Wireless Communication and Security Issues for Cyber–Physical Systems and the Internet-of-Things. Proc. IEEE 106, 1 (2018), 38–60.

[29] MA Burhamuddin, Ali Abdull-Jabar Mohammed, Ronzam Ismail, Mustafa Emad Hameed, Ali Noori Kareem, and Halizah Basiron. 2018. A Review on Security Challenges and Features in Wireless Sensor Networks: IoT Perspective. Journal of Telecommunication, Electronic and Computer Engineering (IETEC) 10, 1-7 (2018), 17–21.

[30] Leela Krishna Bysani and Ashok Kumar Turuk. 2011. A survey on selective forwarding attack in wireless sensor networks. In Devices and Communications (ICDeCom), 2011 International Conference on. IEEE, 1–5.

[31] Bertrand Cambou and Fatemeh Aghafah. 2016. Physically Unclonable Functions with Multi-states and Machine Learning. In 14th International Workshop on Cryptographic Architectures Embedded in Logic Devices (CryptArchi).

[32] Bertrand Cambou and Marius Orłowski. 2016. PUF designed with Resistive RAM and Ternary States. In Proceedings of the 11th Annual Cyber and Information Security Research Conference. ACM, 1.

[33] Bertrand Cambou and Marius Orłowski. 2016. PUF designed with resistive RAM and ternary states. In Proceedings of the 11th Annual Cyber and Information Security Research Conference. ACM, 1.

[34] Srdjan Capkun, Levente Buttyán, and Jean-Pierre Hubaux. 2003. Self-organized public-key management for mobile ad hoc networks. IEEE Transactions on mobile computing 1 (2003), 52–64.

[35] Shaihab Chakrabarty and Daniel W Engels. 2016. A secure IoT architecture for Smart Cities. In 2016 13th IEEE annual consumer communications & networking conference (CCCN). IEEE, 812–813.

[36] Yuan-Hao Chang, Jen-Wei Hsieh, and Tei-Wei Kuo. 2007. Endurance enhancement of flash-memory storage systems: an efficient static wear leveling design. In Proceedings of the 44th annual Design Automation Conference. ACM, 212–217.

Manuscript submitted to ACM
[65] Ian G Harris. 2016. Social Engineering Attacks on the Internet of Things. Pridobijeno iz http://iot.ieee.org/newsletter/september-2016/social-engineering-attacks-on-theinternet-of-things.html (16. 4. 2017) (2016).
[66] Ibrahim Abaker Targio Hashem, Victor Chang, Nor Badrul Anuar, Kayode Adewole, Ibhrar Yaqob, Abdullah Gani, Ejaz Ahmed, and Haruna Chiroma. 2016. The role of big data in smart city. International Journal of Information Management 36, 5 (2016), 748–758.
[67] Nick Heath. 2017. Petya ransomware: Where it comes from and how to protect yourself - TechRepublic. https://www.techrepublic.com/article/petya-ransomware-where-it-comes-from-and-how-to-protect-yourself/. (Accessed on 09/26/2018).
[68] Tobias Heer, Oscar Garcia-Morchon, René Zummenn, SYe Loong Keoh, Sandeep S Kumar, and Klaus Wehrle. 2011. Security Challenges in the IP-based Internet of Things. Wireless Personal Communications 61, 3 (2011), 527–542.
[69] Clemens Helmleiner, Christian Boit, Dmitry Nedospasov, Shahin Tajik, and Jean-Pierre Seifert. 2014. Physical vulnerabilities of physically unclonable functions. In Proceedings of the conference on Design, Automation & Test in Europe. European Design and Automation Association, 359.
[70] Charles Herder, Meng-Duy Yu, Farinaz Koushanfar, and Sriravas Devadas. 2014. Physical unclonable functions and applications: A tutorial. Proc. IEEE 102, 8 (2014), 1126–1141.
[71] Daniel E Holcomb, Wayne P Burleson, Kevin Fu, et al. 2007. Initial SRAM state as a fingerprint and source of true random numbers for RFID tags. In Proceedings of the Conference on RFID Security, Vol. 7. 2.
[72] Md Mahmud Hossain, Mazair Fotouhi, and Ragib Hasan. 2015. Towards an analysis of security issues, challenges, and open problems in the internet of things. In Services (SERVICES), 2015 IEEE World Congress on. IEEE, 21–28.
[73] Urs Hunkeler, Hong Linh Truong, and Andy Stanford-Clark. 2008. MQTT-SÀŤA publish/subscribe protocol for Wireless Sensor Networks. In Communication systems software and middleware and workshops, 2008. comsware 2008. 3rd international conference on. IEEE, 791–798.
[74] Rutvij H Jhaveri, Ashish D Patel, Jatin D Parmar, Bhavin I Shah, et al. 2010. MANET routing protocols and wormhole attack against AODV. International Journal of Computer Science and Network Security 10, 4 (2010), 12–18.
[75] Laurent Joncheray. 1995. A Simple Active Attack Against TCP. In USENIX Security Symposium.
[76] Marc Joye. 2008. On white-box cryptography. Security of Information and Networks (2008), 7–12.
[77] Hyunho Kang, Yohei Hori, Toshihiro Katashita, Manabu Hagawara, and Keichi Iwamura. 2014. Performance analysis for psu data using fuzzy extractor. In Ubiquitous Information Technologies and Applications. Springer, 277–284.
[78] Chris Karlof and David Wagner. 2003. Secure routing in sensor networks: Attacks and countermeasures. Ramesh Karri, Jeyavijayan Rajendran, Kurt Rosenfeld, and Mohammad Tehranipoor. 2010. Trustworthy hardware: Identifying and classifying hardware trojans. Computer 43, 10 (2010), 39–46.
[79] Rafiullah Khan, Sarmad Ullah Khan, Rifagat Zaeber, and Shahid Khan. 2012. Future internet: the internet of things architecture, possible applications and key challenges. In Frontiers of Information Technology (FIT), 2012 10th International Conference on. IEEE, 257–260.
[80] Wazir Zada Khan, Xiang Yang, Mohammed Y Aalsalem, and Quratulain Arshad. 2011. Comprehensive study of selective forwarding attack in wireless sensor networks. International Journal of Computer Network and Information Security 3, 1 (2011), 1.
[81] Steven L Kinney. 2006. Trusted platform module basics: using TPM in embedded systems. Elsevier.
[82] Rowan Kloti, Vasileios Korotinis, and Paul Smith. 2013. Openflow: A security analysis. In Network Protocols (ICNP), 2013 21st IEEE International Conference on. IEEE, 1–6.
[83] Ashwija Korenda, Fatemeh Afghah, Bertrand Cambou, and Christopher Philabaum. 2019. A Proof of Concept SRAM-based Physically Unclonable Function (PUF) Key Generation Mechanism for IoT Devices. In IEEE SECON Workshop on Security, Trust, and Privacy in Emerging Cyber-Physical Systems.
[84] Ashwija Reddy Korenda, Fatemeh Afghah, and Bertrand Cambou. 2018. A secret key generation scheme for internet of things using ternary-states ReRAM-based physically unclonable functions. In 2018 14th International Wireless Communications & Mobile Computing Conference (IWCMC). IEEE, 1261–1266.
[85] Farinaz Koushanfar, Saverio Fazzari, Carl McCants, William Bryson, Peilin Song, Matthew Sale, and Miodrag Potkonjak. 2012. Can EDA combat wireless sensor networks.
[86] Ioannis Krontiris, Thanassis Giannetsos, and Tassos Dimitriou. 2008. Launching a sinkhole attack in wireless sensor networks; the intruder side. In IEEE International Conference on Wireless & Mobile Computing, Networking & Communication 2008. IEEE, 526–531.
[87] Sathish Alampayalaym Kumar, Tyler Vealey, and Harshit Srivastava. 2016. Security in internet of things: Challenges, solutions and future directions. In 2016 49th Hawaii International Conference on System Sciences (HICSS). IEEE, 5772–5781.
[88] Sandeep S Kumar, Jorge Guajardo, Roel Maes, Geert-Jan Schrijen, and Pim Tuyls. 2008. The butterfly PUF protecting IP on every FPGA. In Hardware-Oriented Security and Trust. 2008. HOST 2008. IEEE International Workshop on. IEEE, 67–70.
[89] Klaus Kursawe, Ahmad-Reza Sadeghi, Dries Schellekens, Boris Skoric, and Pim Tuyls. 2009. Reconfigurable physical unclonable functions-enabling technology for tamper-resistant storage. In Hardware-Oriented Security and Trust, 2009. HOST’09. IEEE International Workshop on. IEEE, 22–29.
[90] Paul Leach, Michael Mealling, and Rich Salz. 2005. A universally unique identifier (uuid) urn namespace. Technical Report. Network Working Group.
[91] Kerstin Lemke. 2006. Embedded security: Physical protection against tampering attacks. In Embedded Security in Cars. Springer, 207–217.
[92] Mingyan Li, Iordanis Koutsopoulos, and Radha Poovendran. 2007. Optimal jamming attacks and network defense policies in wireless sensor networks. In INFOCOM 2007. 26th IEEE International Conference on Computer Communications. IEEE, 1307–1315.
[93] Shancang Li, Li Da Xu, and Shanshan Zhao. 2015. The internet of things: a survey. Information Systems Frontiers 17, 2 (2015), 243–259.
Shamsoshoara and Korenda, et al.

[95] Dalihyun Lim, Jae W Lee, Blaise Gassend, G Edward Suh, Marten Van Dijk, and Srinivas Devadas. 2005. Extracting secret keys from integrated circuits. IEEE Transactions on Very Large Scale Integration (VLSI) Systems 13, 10 (2005), 1200–1205.

[96] Huichen Lin and Neil Bergmann. 2016. IoT privacy and security challenges for smart home environments. Information 7, 3 (2016), 44.

[97] Je Liu, Wei Yu, Nan Zhang, Xinyu Yang, Hanlin Zhang, and Wei Zhao. 2017. A survey on internet of things: Architecture, enabling technologies, security and privacy, and applications. IEEE Internet of Things Journal 4, 5 (2017), 1125–1142.

[98] Jing Liu, Yang Xiao, and CL Philip Chen. 2012. Authentication and access control in the internet of things. In Distributed Computing Systems Workshops (ICDCSW), 2012 32nd International Conference on. IEEE, 588–592.

[99] Dongxun Lu and Tao Liu. 2011. The application of IOT in medical system. In IT in Medicine and Education (ITME), 2011 International Symposium on. Vol. 1. IEEE, 272–275.

[100] Yang Lu and Li Da Xu. 2018. Internet of Things (IoT) cybersecurity research: a review of current research topics. IEEE Internet of Things Journal 6, 2 (2018), 2103–2115.

[101] Roel Maes, Pim Tou, and Ingrid Verbaaumhede. 2009. Low-Overhead Implementation of a Soft Decision Helper Data Algorithm for SRAM PUFs. In CHES Vol. 9. Springer, 332–347.

[102] Roel Maes, Anthony Van Herrewege, and Ingrid Verbaaumhede. 2012. PUFY: A fully functional PUF-based cryptographic key generator. Cryptographic Hardware and Embedded Systems–CHES 2012 (2012), 302–319.

[103] Preema Mahajan and Abhishek Sachdeva. 2013. A study of encryption algorithms AES, DES and RSA for security. Global Journal of Computer Science and Technology (2013).

[104] Abhranil Maiti, Inyoung Kim, and Patrick Schaumont. 2012. A robust physical unclonable function with enhanced challenge-response set. IEEE Transactions on Information Forensics and Security 7, 1 (2012), 333–345.

[105] Abhranil Maiti and Patrick Schaumont. 2009. Improving the quality of a physical unclonable function using configurable ring oscillators. In Field Programmable Logic and Applications, 2009. FPL. 2009. International Conference on. IEEE, 703–707.

[106] Michael Manzo, Tanya Roosta, and Shankar Sastry. 2005. Time synchronization attacks in sensor networks. In Proceedings of the 3rd ACM workshop on Security of ad hoc and sensor networks: ACM, 107–116.

[107] Anthéa Mayzaud, Rémi Badonnel, and Isabelle Chrsiment. 2016. A Taxonomy of Attacks in RPL-based Internet of Things. International Journal of Network Security 18, 3 (2016), 459–473.

[108] Diego M. Mendez, Ioannis Papapanagiotou, and Baijian Yang. 2017. Internet of things: Survey on security and privacy. arXiv preprint arXiv:1707.01879 (2017).

[109] Sanaz Rahimi Moosavi, Tuan Nguyen Gia, Amir-Mohammad Rahmani, Ethiopia Nigussie, Seppo Virtanen, Jouni Isoaho, and Hannu Tenhunen. 2015. SEA: a secure and efficient authentication and authorization architecture for IoT-based healthcare using smart gateways. Procedia Computer Science 52 (2015), 452–459.

[110] Sergey Morozov, Abhranil Maiti, and Patrick Schaumont. 2010. An analysis of delay based PUF implementations on FPGA. In International Symposium on Applied Reconfigurable Computing. Springer, 382–387.

[111] Arslan Mosenia and Niraj K Jha. 2017. A comprehensive study of security of internet-of-things. IEEE Transactions on Emerging Topics in Computing 5, 4 (2017), 586–602.

[112] Aristides Mpitziopoulos, Damianos Gavalas, Charalampos Konstantopoulos, and Grammati Pantziou. 2009. A survey on jamming attacks and countermeasures in WSNs. IEEE Communications Surveys & Tutorials 11, 4 (2009).

[113] Steven J Murdoch. 2006. Hot or not: Revealing hidden services by their clock skew. In Proceedings of the 13th ACM conference on Computer and communications security. ACM, 27–36.

[114] SeungJae Na, DongYeo Hwang, WoonSeob Shin, and Ki-Hyung Kim. 2017. Scenario and countermeasure for replay attack using join request messages in LoRaWAN. In 2017 International Conference on Information Networking (ICOIN). IEEE, 718–720.

[115] Mukrimah Nawir, Amiza Amir, Naimah Yaakob, and Ong Bi Lynn. 2016. Internet of Things (IoT): Taxonomy of security attacks. In Information Communications Security. ACM, 586–592.

[116] Bruce Nidhanje, Hoon-Jae Lee, and Sang-Gon Lee. 2014. Security and privacy in the internet of things. Sensors 14, 8 (2014), 14786–14805.

[117] Gavin O’Gorman and Geoff McDonald. 2012. Ransomware: A growing menace. Symantec Corporation.

[118] Ravikanth Pappu, Ben Recht, Jason Taylor, and Neil Gershenfeld. 2002. Physical one-way functions. Science 297, 5589 (2002), 2026–2030.

[119] Al-Sakib Khan Pathan, Hyung-Woo Lee, and Choong Seon Hong. 2006. Security in wireless sensor networks: issues and challenges. In Advanced Communication Technology. 2006. ICACT 2006. The 8th International Conference, Vol. 2. IEEE, 6–pp.

[120] Paolo Pavan, Roberto Bez, Piero Olivo, and Enrico Zanoni. 1997. Flash memory cells—an overview. Proc. IEEE 85, 8 (1997), 1248–1271.

[121] Pavan Pongle and Gurunath Chavan. 2015. A survey: Attacks on RPL and 6LoWPAN in IoT. In Pervasive Computing (ICPC), 2015 International Conference on. IEEE, 1–6.

[122] Alison DeNisco Rayome. 2018. As IoT attacks increase 600% in one year, businesses need to up their security - TechRepublic. https://www.techrepublic.com/article/as-iot-attacks-increase-600-in-one-year-businesses-need-to-up-their-security/. (Accessed on 09/26/2018).

Manuscript submitted to ACM
[124] Mohsen Rezvani, Aleksandar Ignjatovic, Elisa Bertino, and Sanjay Jha. 2015. Secure data aggregation technique for wireless sensor networks in the presence of collusion attacks. *IEEE transactions on Dependable and Secure Computing* 12, 1 (2015), 98–110.

[125] Pankaj Rohatgi. 2009. Electromagnetic attacks and countermeasures. In *Cryptographic Engineering*. Springer, 407–430.

[126] Pankaj Rohatgi. 2009. Improved techniques for side-channel analysis. In *Cryptographic Engineering*. Springer, 381–406.

[127] Tanya Roosta, Shiuhpyng Shieh, and Shankar Sastry. 2006. Taxonomy of security attacks in sensor networks and countermeasures. In *The first IEEE international conference on system integration and reliability improvements*, Vol. 25. 94.

[128] Masoud Rostami, Farinaz Koushanfar, and Ramesh Karri. 2014. A primer on hardware security: Models, methods, and metrics. *Proc. IEEE* 102, 8 (2014), 1283–1295.

[129] Masoud Rostami, Farinaz Koushanfar, Jeyarajvijay Rajendran, and Ramesh Karri. 2013. Hardware security: Threat models and metrics. In *Proceedings of the International Conference on Computer-Aided Design*. IEEE Press, 819–823.

[130] Jarrod A Roy, Farinaz Koushanfar, and Igor L Markov. 2010. Ending piracy of integrated circuits. *Computer* 43, 10 (2010), 30–38.

[131] Sankardas Roy, Sanjeev Setta, and Sushil Jajodia. 2006. Attack-resilient hierarchical data aggregation in sensor networks. In *Proceedings of the fourth ACM workshop on Security of ad hoc and sensor networks*. ACM, 71–82.

[132] Ulrich Rührmair and Daniel E Holcomb. 2014. PUFs at a glance. In *Ulrich Rührmair, Srinivas Devadas, and Farinaz Koushanfar*. 2012. Security based on physical unclonability and disorder. In *Introduction to Hardware Security and Trust*. Springer, 65–102.

[133] Ulrich Rührmair, Christian Hölgers, Sebastian Urban, Agnes Weiershäuser, Elias Dinter, Brigitte Forster, and Christian Jirouschek. 2013. Optical PUFs Reloaded. *Eprint. Iacr*. (2013).

[134] Ulrich Rührmair and Daniel E Holcomb. 2014. PUFs at a glance. In *Proceedings of the conference on Design, Automation & Test in Europe*. European Design and Automation Association, 347.

[135] Ulya Sabeel and Saima Masood. 2013. Categorized security threats in the wireless sensor networks: Countermeasures and security management schemes. *International Journal of Computer Applications* 64, 16 (2013).

[136] Somia Mohamed Saed, Xiaotong Cui, Robert Wille, Alwin Zulehner, Kaijie Wu, Rolf Drechsler, and Ramesh Karri. 2017. Towards reverse engineering reversible logic. *arXiv preprint arXiv:1704.08397* (2017).

[137] Farzad Sami, Vasileios Tsoutsouras, Lars Bauer, Sofiiris Nystis, Dimitrios Soudris, and Jörg Henkel. 2016. Computation offloading and resource allocation for low-power IoT edge devices. In *Internet of Things (WF-IoT), 2016 IEEE 3rd World Forum on*. IEEE, 7–12.

[138] Somitra Kumar Sanadhya and Palash Sarkar. 2008. New collision attacks against up to 26-step SHA-2. In *International conference on cryptography in India*. Springer, 91–103.

[139] Anna Sapienza, Alessandro Bessi, Saranya Damodaran, Paulo Shakarian, Kristina Lerman, and Emilio Ferrara. 2017. Early warnings of cyber threats in online discussions. In *Data Mining Workshops (ICDMW), 2017 IEEE International Conference on*. IEEE, 667–674.

[140] Alexander Schlösser, Dmitry Nedospasov, Juliane Krämer, Susanna Orlic, and Jean-Pierre Seifert. 2013. Simple photonic emission analysis of AES. *Journal of Cryptographic Engineering* 3, 1 (2013), 3–15.

[141] Kai Schramm, Thomas Wollinger, and Christof Paar. 2003. A new class of collision attacks and its application to DES. In *International Workshop on Fast Software Encryption*. Springer, 206–222.

[142] D Senie and P Ferguson. 1998. Network ingress filtering: Defeating denial of service attacks which employ IP source address spoofing. *Network* (1998).

[143] Alireza Shamsoshoara. 2019. Overview of Blakley’s Secret Sharing Scheme. *arXiv preprint arXiv:1903.02802* (2019).

[144] Alireza Shamsoshoara. 2019. Ring Oscillator and its application as Physical Unclonable Function (PUF) for Password Management. *arXiv preprint arXiv:1901.06733* (2019).

[145] Alireza Shamsoshoara and Youssef Darmani. 2015. Enhanced multi-route ad hoc on-demand distance vector routing. In *Electrical Engineering (ICEE), 2015 3rd International Conference on*. IEEE, 578–583.

[146] Alireza Shamsoshoara, Mehrdad Khaleli, Fatemeh Aghfah, Abolfazl Razi, and Jonathan Ashdown. 2019. Distributed cooperative spectrum sharing in uav networks using multi-agent reinforcement learning. In *2019 16th IEEE Annual Consumer Communications & Networking Conference (CCNC)*. IEEE, 1–6.

[147] Alireza Shamsoshoara, Mehrdad Khaleli, Fatemeh Aghfah, Abolfazl Razi, Jonathan Ashdown, and Kurt Turck. 2019. A Solution for Dynamic Spectrum Management in Mission-Critical UAV Networks. *arXiv preprint arXiv:1904.07380* (2019).

[148] Kalpana Sharma and MK Ghose. 2010. Wireless sensor networks: An overview on its security threats. *IJCA, Special Issue on uAIIMobile Ad-hoc NetworksâĂlA MANETS* (2010), 42–45.

[149] Zach Shelby, Klaus Hartke, and Carsten Bormann. 2014. *The constrained application protocol (CoAP)*. Technical Report. IETF.

[150] Zhengguo Sheng, Shusen Yang, Yifan Yu, Athanasios Vasilakos, Julie McCann, and Kin Leung. 2013. A survey on the ietf protocol suite for the internet of things: Standards, challenges, and opportunities. *IEEE Wireless Communications* 20, 6 (2013), 91–98.

[151] Virendra Pal Singh, Sweta Jain, and Jyoti Singh. 2010. Hello flood attack and its countermeasures in wireless sensor networks. *International Journal of Computer Science Issues (IJCSI)*, 7, 3 (2010), 23.

[152] Boris Skoric, Stefan Mauhich, Tom AM Kevenaar, and Pim Tuyls. 2006. Information-theoretic analysis of coating PUFs. *IACR Cryptology ePrint Archive* 2006 (2006), 101.

[153] Boris Skoric, Geert-Jan Schrijen, Wil Ophey, Rob Wolters, Nynke Verhaegh, and Jan van Geloven. 2007. Experimental hardware for coating PUFs and optical PUFs. In *Security with Noisy Data*. Springer, 255–268.

Manuscript submitted to ACM
Brandon Vigliarolo. 2017. WannaCry: A cheat sheet for professionals - TechRepublic. https://www.techrepublic.com/article/wannacry-the-smart-

Mohammad Tehranipoor and Farinaz Koushanfar. 2010. A survey of hardware trojan taxonomy and detection. In Electron Devices Meeting, 2006. IEDM'06. International

Adam Waksman and Simha Sethumadhavan. 2011. Silencing hardware backdoors. In IEEE design & test of computers 27, 1 (2010), 10–25.

Mališa Vučinić, Bernard Tourancheau, Franck Rousseau, Andrzej Duda, Laurent Damon, and Roberto Guizzetti. 2015. OSCAR: Object security

Arunkumar Vijayakumar, Vinay Patil, and Sandip Kundu. 2017. On improving reliability of SRAM-based physically uncloneable functions. In Journal of Low Power Electronics and Applications 7, 1 (2017), 2.

Ying Su, Jeremy Holleman, and Brian P Otis. 2008. A digital 1.6 pJ/bit chip identification circuit using process variations. IEEE Journal of Solid-State Circuits 43, 1 (2008), 69–77.

G Edward Suh and Srinivas Devadas. 2007. Physical uncloneable functions for device authentication and secret key generation. In Proceedings of the 44th annual design automation conference. ACM, 9–14.

G Edward Suh, Charles W O'Donnell, and Srinivas Devadas. 2005. AEGIS: A single-chip secure processor. Information Security Technical Report 10, 2 (2005), 63–73.

Deepak Nandakushma and Vikas Nandak. 2011. Security threats in wireless sensor networks. IFCSMS International Journal of Computer Science & Management Studies 11, 01 (2011), 59–63.

Ibrar Yaqoob, Ejaz Ahmed, Muhammad Habib ur Rehman, Abdelmutthib Ibrahim Abdalla Ahmed, Mohammedi Ali Al-garadi, Muhammad Imran, and Mohsen Guizetti. 2015. OSCAR: Object security architecture for the Internet of Things. Ad Hoc Networks 32 (2015), 3–16.

Adam Waksman and Simha Sethumadhavan. 2011. Silencing hardware backdoors. In 2011 IEEE Symposium on Security and Privacy. IEEE, 49–63.

Wikipedia. 2019. RSA (cryptosystem) - Wikipedia. https://en.wikipedia.org/wiki/RSA_(cryptosystem). (Accessed on 04/26/2019).

Ali Valehi and Abolfazl Razi. 2017. Maximizing energy efficiency of cognitive wireless sensor networks with constrained age of information. IEEE Transactions on Cognitive Communications and Networking 3, 4 (2017), 643–654.

Ali Valehi, Abolfazl Razi, Bertrand Cambou, Weijie Yu, and Michael Koziick. 2017. A graph matching algorithm for user authentication in data networks using image-based physical uncloneable functions. In 2017 Computing Conference. IEEE, 863–870.

Pal Varga, Sandor Ploz, Gabor Soos, and Csaba Hegedus. 2017. Security threats and issues in automation IoT. In Factory Communication Systems (WFCS), 2017 IEEE 13th International Workshop on. IEEE, 1–6.

Brandon Vigliarolo. 2017. WannaCry: A cheat sheet for professionals - TechRepublic. https://www.techrepublic.com/article/wannacry-the-smart-persons-guide/. (Accessed on 09/26/2018).

Arunkumar Vijayakumar, Vinay Patil, and Sandip Kundu. 2017. On improving reliability of SRAM-based physically uncloneable functions. Journal of Low Power Electronics and Applications 7, 1 (2017), 2.

Maláš Vucinich, Bernard Tourancheau, Franck Rousseau, Andrej Duda, Laurent Damon, and Roberto Guizzetti. 2015. OSCAR: Object security architecture for the Internet of Things. Ad Hoc Networks 32 (2015), 3–16.

Adam Waksman and Simha Sethumadhavan. 2011. Silencing hardware backdoors. In 2011 IEEE Symposium on Security and Privacy. IEEE, 49–63.

Wikipedia. 2019. RSA (cryptosystem) - Wikipedia. https://en.wikipedia.org/wiki/RSA_(cryptosystem). (Accessed on 04/26/2019).

Khin Sandar Win. 2008. Analysis of detecting wormhole attack in wireless networks. In World Academy of Science, Engineering and Technology. Citeseer.

Marilyn Wolf and Dimitrios Serpanos. 2018. Safety and security in cyber-physical systems and Internet-of-Things systems. Proc. IEEE 106, 1 (2018), 9–20.

Anthony D Wood and John A Stankovic. 2002. Denial of service in sensor networks. computer 35, 10 (2002), 54–62.

Xue Yang, Zhuhua Li, Zhenmin Geng, and Haitao Zhang. 2012. A multi-layer security model for internet of things. In Internet of things. Springer, 388–393.

Ibrar Yaqoob, Ejaz Ahmed, Muhammad Habib ur Rehman, Abdelmutthib Ibrahim Abdalla Ahmed, Mohammed Ali Al-garadi, Muhammad Imran, and Mohsen Guizetti. 2015. The rise of ransomware and emerging security challenges in the Internet of Things. Computer Networks 128 (2017), 444–458.

Ning Ye, Yan Zhu, Ru-chuan Wang, Reza Malekian, and Lin Qiao-min. 2014. An efficient authentication and access control scheme for perception layer of internet of things. Applied Mathematics & Information Sciences 8, 4 (2014), 1617.

Ping Yi, Zhoulin Dai, Yiping Zhong, and Shiyong Zhang. 2005. Resisting flooding attacks in ad hoc networks. In Information technology: Coding and computing. 2005. ITCC 2005. International conference on, Vol. 2. IEEE, 657–662.
A Survey on Hardware-based Security Mechanisms for Internet of Things

[184] Mustafa Harun Yılmaz and Hüseyin Arslan. 2015. A survey: Spoofing attacks in physical layer security. In *Local Computer Networks Conference Workshops (LCN Workshops)*, 2015 IEEE 40th. IEEE, 812–817.

[185] Chi-En Yin and Gang Qu. 2009. Temperature-aware cooperative ring oscillator PUF. In *Hardware-Oriented Security and Trust, 2009. HOST ’09. IEEE International Workshop on*. IEEE, 36–42.

[186] Bo Yu and Bin Xiao. 2006. Detecting selective forwarding attacks in wireless sensor networks. In *Parallel and distributed processing symposium, 2006. IPDPS 2006. 20th international*. IEEE, 8–pp.

[187] Kuan Zhang, Xiaohui Liang, Rongxing Lu, and Xuemin Shen. 2014. Sybil attacks and their defenses in the internet of things. *IEEE Internet of Things Journal* 1, 5 (2014), 372–383.

[188] Lichen Zhang, Zhipeng Cai, and Xiaoming Wang. 2016. Fakemask: A novel privacy preserving approach for smartphones. *IEEE Transactions on Network and Service Management* 13, 2 (2016), 335–348.

[189] Zhi-Kai Zhang, Michael Cheng Yi Cho, Chia-Wei Wang, Chia-Wei Hsu, Chong-Kuan Chen, and Shihpyng Shieh. 2014. IoT security: ongoing challenges and research opportunities. In *Service-Oriented Computing and Applications (SOCA), 2014 IEEE 7th International Conference on*. IEEE, 230–234.

[190] Kai Zhao and Lina Ge. 2013. A survey on the internet of things security. In *Computational Intelligence and Security (CIS), 2013 9th International Conference on*. IEEE, 663–667.

[191] Thomas Ziola, Zdenek Paral, Srinivas Devadas, Gookwon Edward Suh, and Vivek Khandelwal. 2014. Authentication with physical unclonable functions. *US Patent 8,782,396.*