



# Current research on Internet of Things (IoT) security: A survey

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## ABSTRACT

The results of IoT failures can be severe, therefore, the study and research in security issues in the IoT is of extreme significance. The main objective of IoT security is to preserve privacy, confidentiality, ensure the security of the users, infrastructures, data, and devices of the IoT, and guarantee the availability of the services offered by an IoT ecosystem. Thus, research in IoT security has recently been gaining much momentum with the help of the available simulation tools, modellers, and computational and analysis platforms. This paper presents an analysis of recent research in IoT security from 2016 to 2018, its trends and open issues. The main contribution of this paper is to provide an overview of the current state of IoT security research, the relevant tools, IoT modellers and simulators.

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## 1. Introduction

The Internet of Things (IoT) is envisioned to grow rapidly due to the proliferation of communication technology, the availability of the devices, and computational systems. Hence, IoT security is an area of concern in order to safeguard the hardware and the networks in the IoT system. However, since the idea of networking appliances is still relatively new, security has not been considered in the production of these appliances.

Some examples of existing IoT systems are self-driving vehicles (SDV) for automated vehicular systems, microgrids for distributed energy resources systems, and Smart City Drones for surveillance systems. A microgrid system represents a good example of a cyber-physical system: it links all distributed energy resources (DER) together to provide a comprehensive energy solution for a local geographical region. However, a microgrid IoT system still relies on traditional Supervisory Control and Data Acquisition (SCADA). The integration of the physical and cyber domains actually increases the exposure to attacks: cyber attacks may target the SCADA supervisory control and paralyse the physical domain or the physical devices may be tampered or compromised, affecting the supervisory control system. On the other hand, the drone market is moving quickly to adopt automation techniques and can be integrated into fire fighting, police, smart city surveillance, and emergency response. As municipalities and citizens begin to rely on such a system, it will become critical to keep the system secure and reliable.

In recent years, it has been observed that academic research to address the privacy and security issues for IoT systems has at-

tained positive developments. Currently, the techniques and security methods which have been proposed are essentially based on conventional network security methods. However, applying security mechanisms in an IoT system is more challenging than with a traditional network, due to the heterogeneity of the devices and protocols as well as the scale or the number of nodes in the system. The challenges in applying IoT security mitigation which are due to physical coupling, heterogeneity, resource constraints, privacy, the large scale, trust management and unpreparedness for security are extensively explained in [1].

The survey papers [2–6] evaluate the possible threats to IoT systems according to the layers and the available countermeasures. Kouicem et al. [7] stated that in recent years, there has been a lot of research to address issues such as key management, confidentiality, integrity, privacy, and policy enforcement for IoT systems, hence suggested traditional cryptography methods and new technologies such as Software Defined Network (SDN) and Blockchain to be implemented to solve current IoT security issues.

One of the key enablers of the rapid progress of academic IoT security research is the availability of a tool for IoT or sensor network simulation and modelling. A comprehensive list of the simulators used in current research is presented by Chernyshev et al. [8]. An open source network simulator, such as NS 3, is the most used simulator for IoT security research. However, since many new security protocols are being proposed, there is an urgent need for a security protocol evaluator, such as Automated Validation of Internet Security Protocols and Applications, AVISPA.

The present paper will survey the current development of IoT security research from 2016 to 2018. Challenges in applying security mechanisms in IoT and its attack vectors will also be evaluated. Simulators or IoT modellers that may be used by new researchers to further develop the IoT security field will be highlighted. The

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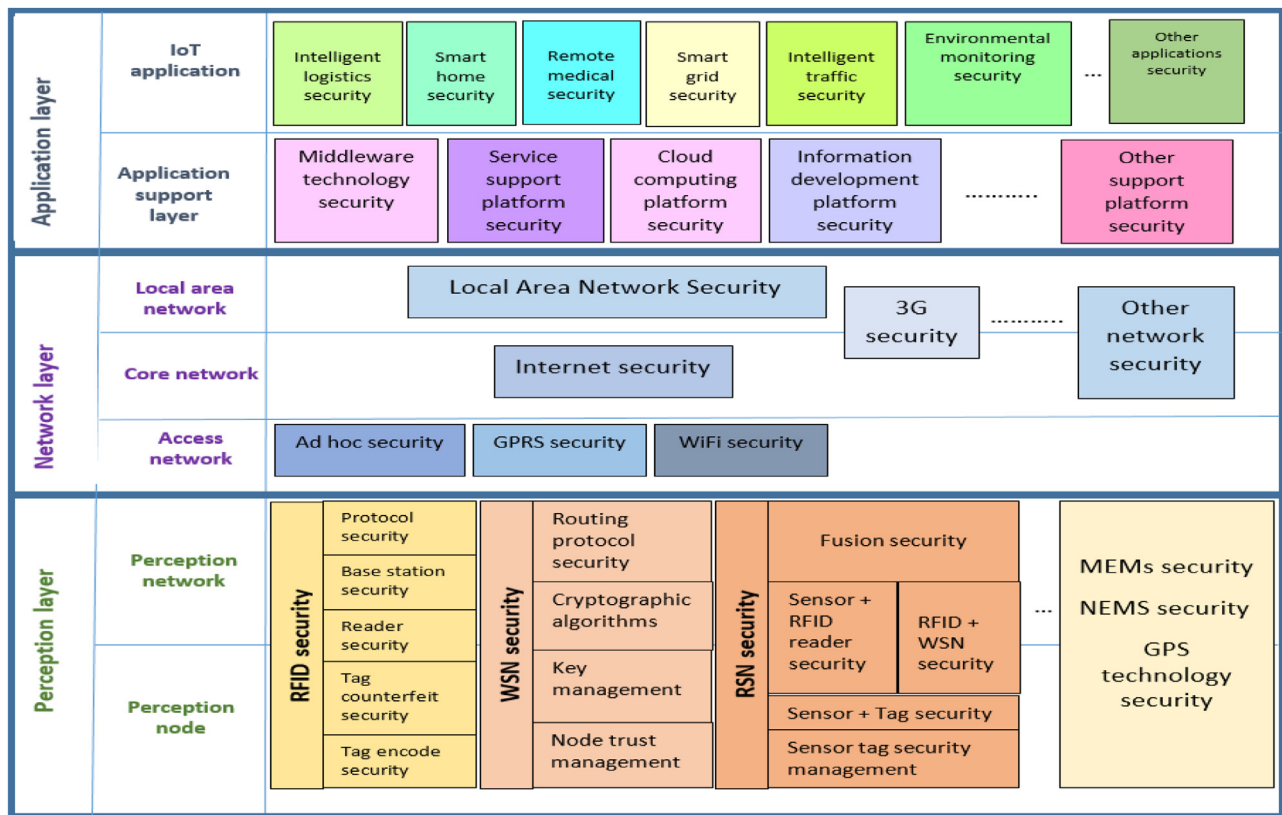


Fig. 1. Typical IoT security architecture.

In addition to the current services, the emergence of new communication technologies, such as 5G, will make the role of the Cloud become more significant. 4G and 5G cellular connectivity allows long range wireless communication. Moreover, the ability to make all IoT devices addressable by using IPV6, enables the IoT devices to be connected directly to the Cloud.

### 3. Introduction to IoT security

Due to the diversity of the devices and multitude of communication protocols in an IoT systems, and also various interfaces and services offered, it is not suitable to implement security mitigation based on the traditional IT network solutions. In fact, the current security measures which are applied in a conventional network may not be sufficient. Attack vectors as listed by Open Web Application Security Project (OWASP) concern the three layers of an IoT system, which are hardware, communication link and interfaces/services. Hence, the implementation of IoT security mitigation should encompass the security architecture at all IoT layers, as presented in Fig. 1. Radio Frequency Identification (RFID) and Wireless Sensor Network (WSN) are considered as part of an IoT network. Thus, possible attacks on these two systems are presented in Table 2.

#### 3.1. IoT attack vectors

Referring to the IoT security architecture, IoT security issues are pertinent at all three IoT layers. For instance, lack of transport encryption concerns an insecure communication link between device and the Cloud, device and gateway, device and mobile applications, one device and another device, and communication between the gateway and the Cloud.

A very popular vector for gaining access to IoT devices arises due to inadequate authentication and authorization procedures. In

the current IoT systems, the protocols that support authentication are MQTT, DDS, Zigbee and Zwave. Nevertheless, even if the developer has provided the authentication tools required for IoT communications, pairing and messaging, there are still opportunities for the communication to be hijacked. Furthermore, insecure network services may cause the bad actor or the threat to explore the network and propagate through it. Currently, authentication is the most popular security method to achieve secure communication in the network layer. Even though there are issues of impracticality due to the devices' constraints, some researchers suggest implementing IPSec in the IoT environment through the adaptation layer. There is also ongoing research to produce lightweight authentication based on public key management. Research in authentication will be extensively discussed in the next section.

Insufficient security configurability is due to the hardcoded credentials which are often used within IoT devices. Hardcoded credentials are easy to compromise due to the use of the same password by many devices. Poor physical security is another attack vector caused by vulnerability in the hardware. The main obstacle in encrypting the devices is due to the simplicity of devices such as sensors. Furthermore, there might be a conflict in terms of the usability of the product. However, it might be worthwhile to implement lightweight encryption in devices to ensure the confidentiality and security of the users.

Insecure web and cloud interfaces are vulnerabilities that may be an attack vector in an IoT system at the application layer. Thus, the cloud gateways have to be equipped with security controls to restrict bad actors from modifying configurations. Applying biometrics and multi-level authentication for access control might be a good solution at the application layer. Due to the changing trends in security threats, [2] has suggested current security challenges according to the layer and the possible countermeasures. Some current challenges and the proposed countermeasures are presented in Table 3. [4]

**Table 2**  
Possible Attacks on WSN and RFID.

|                    | RFID attacks  | WSN attacks   |
|--------------------|---|---|
| Layer              | Possible attacks  | Possible attacks  |
| Physical/Link      | Jammers, replay attacks, Sybil, selective forwarding, synchronization attack.   | Passive interference, active jamming of temporarily disabling the device, Sybil, destruction of RFID readers, replay attacks    |
| Network/Transport  | Sinkhole, unfairness, false routing, hello and session flooding, eavesdropping. | <b>Tag attacks:</b> Cloning, spoofing<br><b>Reader attacks:</b> Impersonation, eavesdropping<br><b>Network protocol attacks</b> |
| Application Layer  | Injection, buffer overflows   | Injection, buffer overflows, unauthorized tag reading, tag modification   |
| Multi-layer attack | Side channel attack, replay attacks, traffic analysis, crypto attack            | Side channel attack, replay attacks, traffic analysis, crypto attack  |

**Table 3**  
Current challenges in IoT security and the proposed countermeasures [2].

| Layer       | Security challenges  | Mitigation   |
|-------------|--|--|
| Perception  | Detection of the abnormal sensor node<br>The choice cryptography algorithms and key management mechanism to be used<br><br>Data and sender anonymity<br>Device vulnerabilities | fault detection algorithm, decentralized intrusion detection system<br>public key encryption due to the large scale network<br>slot reservation protocol<br>Access control, mitigation of resource depletion attacks |
| Network     | Enabling IPSec communication with IPv6 nodes   | Research in the suitability of IPv6 and IPSec for secure communication.  |
| Application | Configurable embedded computer systems.  | No suggestion is available from this paper   |

Securing IoT systems presents a number of unique challenges, such as unreliable communications, hostile environments, and inadequate protection of data and privileges [9].

As shown in Table 3, there are more security challenges at the perception layer. This may be for several reasons, such as easy physical access to the end nodes, vulnerable devices' web interfaces, and unsecured network services. Hence, it can be concluded that for IoT systems, physical devices or the end-nodes are the main attack surface for the adversaries.

#### 4. Development of current IoT security mechanisms

The main objective of applying security mitigation is to preserve privacy, confidentiality, ensuring the security of the users, infrastructures, data and devices of the IoT and to guarantee the availability of the services offered by an IoT ecosystem. Thus, the mitigation and countermeasures are usually applied according to the classic threat vectors. Fig. 2 shows the trends in the techniques and methods which have been used in 2016–2018. It is observed that authentication is still the most popular technique for security, while trust management is gaining popularity, due to its ability to prevent or detect malicious node. On the other hand, research on encryption is focussing on lightweight and low-cost encryption for low-power and constrained devices.

##### 4.1. Authentication

Authentication is the process of identifying users and devices in a network and granting access to authorized persons and non-manipulated devices. Authentication is one way to mitigate attacks to the IoT systems such as the reply attack, the Man-in-the-Middle attack, the impersonation attack, and the Sybil attack. As shown in the graph in Fig. 3, authentication is currently still the most popular method (60%) to grant access to the user at the application layer and also give access to the device in the IoT network.

Transport layer Security (TLS) is widely used for communication authentication and encryption. Specifically for constrained devices, TLS offers TLS-PSK, which uses pre-shared keys, and TLS-DHE-RSA authentication method which uses RSA and Diffie-Hellman (DH) key exchange, which are public key and cryptographic protocols. In this scheme, the two entities that are to perform mutual authentication must prove their legitimacy to each other by sharing secret information (pre-shared keys) beforehand. Since only symmetric key encryption is used in the authentication process, the scheme is suitable for constrained devices such as sensors [10]. Currently, there are three types of authentication protocols designed for IoT: asymmetric-cryptosystem based protocols (Table 5), symmetric-cryptosystem based protocols (Table 6), and hybrid protocols [11].

Since the users and devices in an IoT environment create two-way communication, there is a mutual communication between the device and the servers. The device will send data to the server as well as receive control data transmitted by the server. As such, mutual authentication is crucial in an IoT system to check the validity of both the device and the server. Mutual authentications are in [12–15]. Recently, there has been a huge demand for lightweight authentication and encryption. In [13,14,16–22], the aim is to provide lightweight authentication for access control and secure communication. Multi-factor authentication by using bio-hashing and anonymity are other ways to achieve IoT authentication's goal, as suggested by [12,23,24] and [15]. Fig. 4 presents current trends in IoT authentication methods from 2016 to 2018.

##### 4.1.1. Weaknesses of IoT authentication methods

Due to the challenges in an IoT system, such as scalability, constrained devices, heterogeneous protocols and communication channels, applying authentication as a security mechanism may face several challenges, which are discussed briefly in this section.

The Key Agreement (LKA) protocol is proposed by [22]. It is based on the Internet Key Exchange (IKEV2). This protocol is de-

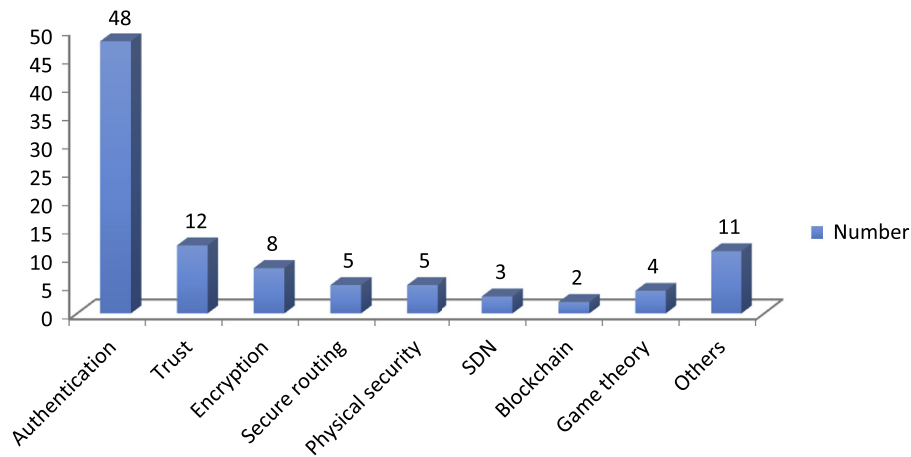


Fig. 2. Publications in IoT security from 2016 to 2018

\*Publications from Elsevier, IEEE, Hindawi and Springer from 2016 until June 2018.

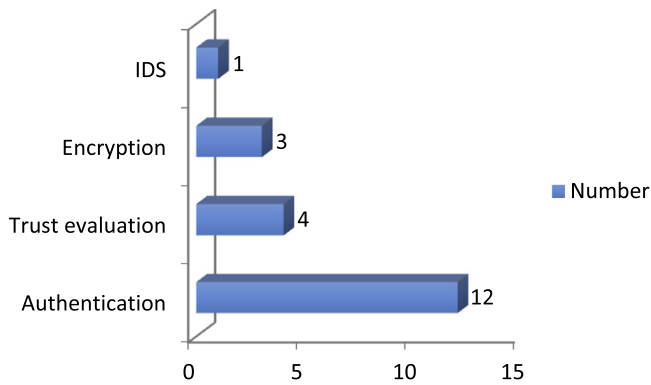


Fig. 3. Access control method according to the current IoT research.

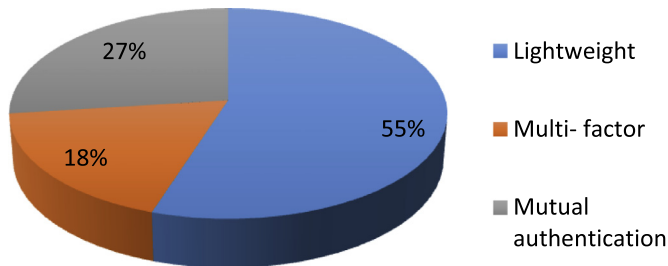


Fig. 4. Research trends on authentication.

signed to provide end-to-end security between IPv6 and 6LoWPAN nodes. However, this protocol is only applicable to IP based devices, which need to be equipped with the relevant authentication tools. On the other hand, lightweight cryptographic functions to provide lightweight and privacy-preserving mutual authentication are proposed by [14]. However, the devices need to be synchronized with the cloud server and the proposed scheme does not support dynamicity.

A secure and efficient user authentication scheme for multi-gateway wireless sensor networks is proposed by [25]. The proposed scheme supports the scalability and dynamics of a WSN without affecting the functionality of the registration or authentication process of both the user and sensor nodes and mutual authentication. Despite the advantages of the scheme, the proposed scheme has a higher computational overhead than other lightweight authentication schemes.

An enhanced authentication and key establishment scheme is designed for M2M communications in the 6LoWPAN networks (EAKES6Lo) [17]. In the proposed scheme, a hybrid cryptography approach is employed for secure authentication and flexible key establishment in the resource constrained 6LoWPAN nodes. Even though the proposed security scheme supports both static and mobile nodes in 6LoWPAN networks, the authentication scheme is energy consuming for resource-constrained devices.

An end-to-end security protocol for 6LoWPAN (6LowPsec) [16] performs security functions (cipher, integrity check, authentication etc.) only at end devices, especially for a 6LoWPAN border router, without requiring any additional network security functions. The proposed protocol is implemented at the adaptation layer and requires minimum overhead, processing, and minimum control information exchange.

A two-factor authentication and key agreement scheme in 5G-integrated WSNs for the IoT is proposed in [15] in order to support anonymity for mitigating offline password guessing attacks and other relevant attacks due to the inefficiency of the authentication process. Due to its higher computational and communication cost, the proposed authentication scheme might not be applicable to normal sensor nodes.

However, all the proposed authentications are a form of one-time process and the use of a public key for lightweight authentication is still not the ultimate solution for security mitigation since a public key can be stolen [26]. Moreover, authentication may be bypassed by some malicious codes or statements. In [22] and [15] the weaknesses of the current solutions for IoT authentication are elaborated as listed below:

- 1) Stolen verifier attack and many logged-in users with the same login ID attack.
- 2) Denial-of-service attack and node capture attack.
- 3) Replay attack and forgery attack.
- 4) Stolen smart-card and sensor-node impersonation.
- 5) Gateway node bypassing and sensor-node key impersonation.
- 6) Off-line password guessing attack, off-line identity guessing attack, smart card theft attack, user impersonation attack, sensor node impersonation attack.

Even though authentication is still considered the primary security mechanism for most IoT systems, it still has weaknesses and flaws and may not be a holistic solution for IoT security mitigation. However, it is still worthwhile to look into some of the current authentication mechanisms proposed from 2016 to 2018, as presented in Table 4.



**Table 4**  
Recent research on authentication.

| Ref  | Layer       | Device Centric |     | Lightweight | U2M | M2M | Security objective             | Domain            | Advantage  | Simulator/Computation/<br>Analysis tools |
|------|-------------|----------------|-----|-------------|-----|-----|--------------------------------|-------------------|--|--|
| [15] | Network     | No             |     | Yes         | Yes | Yes | Secure Communication           | Generic           | Overhead is reduced  | Cooja                                    |
| [17] | Network     | Yes            |     | No          |     | Yes | Secure Communication           | Generic           | Support both mobile and static nodes, mutual authentication                                  | MATLAB                                   |
| [27] | Network     | Yes            |     | No          | No  | Yes | Secure Communication           | Generic           | Mutual authentication, three factor authentication   | NS3                                      |
| [28] | Network     | Yes            |     | No          | Yes | Yes | Secure Communication           | Generic           | Improve key management and use AES-GCM one pass authentication for data integrity            | Not available                            |
| [23] | Application | Yes            |     | Yes         | Yes | No  | Access Control                 | Generic           | Multi-factor authentication, lightweight biometric authentication and key agreement          | AVISPA                                   |
| [13] | Network     | Yes            |     | Yes         | Yes | No  | Access Control                 | WSN               | Mutual authentication, novel authentication and key agreement based on bio-hashing           | AVISPA                                   |
| [29] | Network     | Yes            |     | No          | No  | Yes | Access Control                 | Vehicular network | Capacity based access admission control  | MATLAB                                   |
| [30] | Network     | Yes            |     | No          | No  | Yes | Secure Communication           | WSN               | Authentication scheme for multi gateway WSN  | NS2                                      |
| [31] | Network     | Yes            |     | No          | Yes | No  | Access Control                 | Generic           | Three factor UAKMP   | AVISPA                                   |
| [18] | Network     | Yes            |     | Yes         | No  | Yes | Access Control                 | Generic           | Ultra weight RFID authentication protocol  | C++                                      |
| [32] | Network     | Yes            | No  |             | Yes | Yes | Access Control                 | Medical           | Use elliptic curve crypto system to generate symmetric secure key                            | Cooja                                    |
| [33] | Application | Yes            | No  |             | No  | Yes | Identification                 | Medical           | Use NFC and suitable for mobile environment  | NS2                                      |
| [34] | Network     | Yes            | No  |             | Yes | Yes | Access Control                 | Medical           | Interpret users' biometric signal  | NS2                                      |
| [35] | Network     | Yes            | Yes |             | No  | Yes | Secure communication           | Generic           | Unidirectional and bidirectional IP or non-IP devices  | MATLAB                                   |
| [24] | Application | Yes            | No  |             | Yes | No  | Access Control                 | Generic           | Three factor authentication using bio-hashing  | AVISPA                                   |
| [36] | Network     | Yes            | No  |             | No  | Yes | Secure Communication           | Generic           | Security enhanced group based (SEGB)   | AVISPA                                   |
| [36] | Application | No             | No  |             | Yes | No  | Access Control                 | Generic           | Parallel matching mechanism and cloud computing based resolution                             | Prototype available                      |
| [37] | Network     | Yes            | No  |             | No  | Yes | Secure Communication           | Generic           | Secure network coding signatures   | Not available                            |
| [20] | Application | Yes            | Yes |             | Yes | No  | Access Control                 | Smart Home        | Lightweight authorization for un-trusted Cloud Platform                                      | Test-bed                                 |
| [13] | Network     | No             | No  |             | Yes | No  | Access Control                 | WSN               | Bio hashing authentication   | AVISPA                                   |
| [38] | Network     | Yes            | No  |             | Yes | No  | Access Control                 | Generic           | New signature based authentication key establishment   | AVISPA                                   |
| [39] | Application | No             | No  |             | Yes | No  | Access Control                 | BAN               | Authentication protocol by using smart card  | BAN-logic and AVISPA                     |
| [40] | Network     | Yes            | Yes |             | No  | Yes | Secure communication           | BAN               | Mutual authentication  | Not Available                            |
| [21] | Physical    | Yes            | Yes |             | No  | Yes | Attestation and identification | Generic           | Software integrity, mutual authentication and tamper proof feature for smart embedded object | Prototype                                |
| [41] | Physical    | Yes            | Yes |             | No  | Yes | Secure communication           | Generic           | Social networking based authentication (SNAuth) protocol                                     | OPNET                                    |
| [42] | Network     | Yes            | No  |             | No  | Yes | Secure communication           | Generic           | Identity based AKE protocol  | Not available                            |
| [43] | Network     | Yes            | No  |             | No  | Yes | Secure communication           | Generic           | No pre configured security information is needed   | MICA2                                    |
| [44] | Application | No             | No  |             | Yes | No  | Access Control                 | Medical           | Provide user anonymity   | Test-bed                                 |
| [10] | Network     | Yes            | No  |             | No  | Yes | Secure Communication           | Generic           | ID-based key sharing scheme to TLS   | Not available                            |
| [22] | Application | No             | Yes |             | Yes | No  | Access control                 | Generic           | Certificate free authentication  | MATLAB                                   |
| [45] | Network     | Yes            | No  |             | No  | Yes | Secure Communication           | VANET             | certificate-less authentication  | Not available                            |

**Table 5**  
Asymmetric lightweight cryptography algorithms for IoT [47].

| Asymmetric algorithm | Key size | Code length | Possible attack |
|----------------------|----------|-------------|-----------------|
| RSA                  | 1024     | 900         | Modules attack  |
| ECC                  | 160      | 8838        | Timing attack   |

#### 4.2. Encryption

In achieving end to end security, the nodes are encrypted. However, due to the heterogeneity of the IoT systems, some nodes might be able to embed general purpose micro processors. However, low resources and constrained devices can only embed application-specific ICs [46]. Hence, conventional cryptographic primitives are not suitable for low-resource smart devices due to their low computation power, limited battery life, small size, small memory, and limited power supply. Thus, lightweight cryptography may be an efficient encryption for these devices.

Since the goal for IoT encryption is to achieve efficient end to end communication with low power consumption, symmetric and asymmetric lightweight algorithms for IoT are designed to meet the requirements [47]. Research in [48–50] has focussed on implementing low cost and lightweight encryption in the physical and the network. On the other hand, an attribute based decryption system is proposed by [49] to support user revocation. A summary of recent research on encryption is presented in Table 7.

#### 4.3. Trust management

There has been an increasing amount of publications on devices' trust management. The objective of IoT trust management is to detect and eliminate malicious nodes and to provide secure access control. Automated and dynamic trust calculations to validate the trust values of the participating nodes in an IoT network are among the state of the art in trust management research. However, most of the research focuses on detecting the malicious nodes; only a few trust based access control method have been proposed. Indeed, due to scalability and the huge number of smart things which hold sensitive data, there is an urgent need for an automated, transparent and easy access control management, so that different access level can be given to different nodes/users [56].

Even though only 20% (refer to Fig. 3) of the access control methods currently use trust evaluation, it is still a promising security mechanism. This may be due to its ability to calculate a node's dynamic trust score [57]. This enables the trust value of each node to be progressively evaluated. Moreover, Caminha et al. in [58] have proposed smart trust evaluation by using Machine Learning (ML). This may be able to mitigate the on-off attack which threatens the node's trust value. In addition, trust management might be able to complement the obvious weakness of authentication, such as attacks from the corrupted nodes.

Zhang et al. [59] state that trust computing for access control in an IoT network, Trust-Based Access Control (TBAC), is still relatively new but has been implemented successfully in commercial

applications. Bernal et al. [60] proposed a trust-aware control system for IoT that promotes multidimensional trust properties. Due to the devices' resource constraints, the trust evaluation is centralized as in many proposals, see Table 8.

#### 4.4. Secure routing

Sensors and actuators are important elements in an IoT network. Even though these devices are usually low-powered and resource constrained, they are self-organized and share information. At the same time, they also act as data storage and perform some computations. Hence, scalability, being able to be autonomous, and energy efficiency are important for any routing solution. Some of these sensor nodes are border routers to connect the low power lossy network (LLN) to the internet or to a close by Local Area Network (LAN). Due to the large scale of the IoT networks, the IP addresses for these devices are based on IPv6. IPv6 over low power wireless personal area networks (6LoWPAN) is an IETF IPv6 adaptation layer that enables IP connectivity over low power and lossy network. However, since there is no authentication at the 6LoWPAN layer, there is a high likelihood of a security breach [69].

RPL (Low power and lossy network protocol) is designed for multipoint communication while supporting both point to point and multi point communication in an LLN. DODAG (Destination Oriented Directed Acyclic Graph) is the RPL topology for the nodes' routing protocol. Even though RPL meets all the routing requirements of LLNs, it is susceptible to many security attacks, as summarized in Table 9.

In order to launch a Sinkhole, Blackhole or Sybil attack, a malicious node will try to find a way to participate in the routing or forwarding path of the data and control packets. Thus, it will exploit the vulnerabilities of the routing protocols which are designed with the assumption that all the participating nodes are trustworthy [71].

A secure and efficient protocol for route optimization is proposed in [72]. The proposed protocol is to optimize the existing routing protocol in Proxy Mobile IPv6 (PMIPv6) in a Smart Home network. The protocol supports mutual authentication, key exchange, perfect forward secrecy, and privacy. A novel secure-trust aware RPL routing protocol (SecTrust-RPL) which is based on the trust mechanism is proposed and implemented in [73]. The proposed protocol is to provide protection against Rank and Sybil attacks while optimizing network performance.

A secure time synchronization model for large-scale IoT is proposed in [27], in which a node uses its father node and grandfather node to detect any malicious node. A secure and trust-based approach to mitigate the Blackhole attack on AODV based MANET is proposed in [74].

Even though the efficiency of the proposed protocols is evaluated and performance metrics such as throughputs are increased, the end to end delay may increase due to isolation and the computational process and may not support scalability and mobility, which are critical aspects of an IoT system.

Due to the vulnerabilities of a RPL routing protocol, current related work for secure routing is presented in Table 10.

**Table 6**  
Symmetric lightweight cryptography algorithms for IoT [47].

| Symmetric algorithm | Code length | Structure | Number of rounds | Key size | Block size | Possible attacks          |
|---------------------|-------------|-----------|------------------|----------|------------|---------------------------|
| AES                 | 2606        | SPN       | 10               | 128      | 128        | Man-in-the-middle attacks |
| HEIGHT              | 5672        | GFS       | 32               | 128      | 64         | Saturation attack         |
| TEA                 | 1140        | Feistel   | 32               | 128      | 64         | Related key attack        |
| PRESENT             | 936         | SPN       | 32               | 80       | 64         | Differential attack       |
| RC5                 | Not fixed   | ARX       | 20               | 16       | 32         | Differential attack       |

**Table 7**

Current research on encryption based solution.

| Ref  | Layer       | Security objective                 | Domain     | Advantage  | Simulator/Computation/<br>Analysis tools |
|------|-------------|------------------------------------|------------|--|--|
| [48] | Physical    | Secure 802.15.4 transceiver design | Generic    | Reduces computations at the upper layer and mitigate multiple attacks  | ASIC UMC 018 u CMOS and FPGA prototype   |
| [49] | Network     | To maintain data confidentiality   | Generic    | Low cost   | Not available                            |
| [51] | Application | Access control                     | Generic    | Attribute based decryption with user revocation                        | MICA                                     |
| [52] | Network     | To prevent energy depletion        | Generic    | Accurate localization of the attacker                                  | Test-bed                                 |
| [53] | Physical    | Data protection                    | Generic    | High-speed ultra low-power low energy with multiple levels of security | Test-bed                                 |
| [50] | Network     | Data protection                    | Generic    | Lightweight  | NS2                                      |
| [54] | Physical    | Secure communication               | Industrial | Detect multiple counterfeit ICs  | Prototype                                |
| [55] | Physical    | Access control                     | WBAN       | Heterogeneous sign-cryption scheme                                     | Not available                            |

**Table 8**

Current research on trust based solution.

| Ref  | Layer   | Centralized | Decentralized | Advantage   | Simulator/Computation/Analysis tools |
|------|---------|-------------|---------------|---|--------------------------------------|
| [61] | Network | Yes         |               | Trust computation defines the direct trust of a node on its neighbour.    | Not available                        |
| [57] | Network |             | Yes           | Dynamic trust calculation   | NS3                                  |
| [62] | Network | Yes         |               | More reliable trust calculation   | NS3, MATLAB                          |
| [63] | Network |             |               | Semi distributed  | MATLAB                               |
| [64] | Network | Yes         |               | Time based trust aware routing protocol                                   | Cooja                                |
| [65] | Network | Yes         |               | Lightweight trust evaluation for the nodes to detect malicious node       | MATLAB                               |
| [66] | Network | Yes         |               | Trust evaluation is based on nodes' behaviour and historical trust.       | OMNET++                              |
| [67] | Network |             | Yes           | Trust management from devices' property by using Fuzzy approach           | MATLAB Fuzzy Toolbox                 |
| [58] | Network | Yes         |               | Smart trust management by using Machine Learning and elastic slide window | Cooja                                |
| [68] | Network |             | Yes           | Multi domain RFID system  | NS3                                  |

**Table 9**

Attacks on RPL [70].

| Attack               | Effect on network parameter   |
|----------------------|---|
| Selective forwarding | Disrupt routing path  |
| Sinkhole             | Large traffic flows through attacker node                                 |
| Hello flooding       | Route formation through attacker node                                     |
| Warmhole             | Disrupt the network topology and traffic flow                             |
| Sybil and clone ID   | Routing traffic unreachable to victim node                                |
| Denial of service    | Make resources unavailable to intended users                              |
| Blackhole            | Packet delay and control overhead   |
| Rank                 | Packet delay, delivery ratio and generation of un-optimized path and loop |
| Version number       | Control overhead, delivery ratio, end to end delay                        |
| Local repair         | Control overhead, disrupt routing and traffic flow                        |
| Neighbour and DIS    | Packet delay  |



**Table 10**  
Recent research on secure routing.

| Ref  | Objective                         | Method  | Simulator/Computation/Analysis tools |
|------|-----------------------------------|---|--------------------------------------|
| [75] | Secure routing                    | Mutual authentication, key exchange, perfect forward secrecy and privacy.             | AVISPA                               |
| [27] | Anomaly detection                 | Secure time synchronization model   | NS2                                  |
| [76] | To prevent gray-hole attack       | Enhanced DCFM method  | NS3                                  |
| [64] | To mitigate rank and Sybil attack | Time-based trust aware RPL (SecTrust RPL)   | Cooja                                |
| [77] | Data confidentiality              | Hybrid control channel based cognitive AODV/routing protocol with directional antenna | NS2                                  |

#### 4.5. New technology

There are two types of new technology which have been of interest recently. SDN (software defined network) and blockchain are among the popular new technologies that converge with IoT security solutions. The main idea of SDN is to separate the network control and the data control. Thus, both centralized control and dynamic management of the network are possible, in order to deal with obstacles in the IoT environment such as resource allocation in IoT devices. Furthermore some current challenges in IoT, such as reliability, security, scalability and QoS might be able to be addressed efficiently.

Block chain is the backbone of cryptocurrency. IoT based applications will take the advantage of its secure and private transactions, as well as its decentralization of communications and processes. To date, its application has achieved significant success in financial applications. Decentralization, pseudonymity and secure transactions are among the advantages of blockchain technology for the IoT.

Kim et al. [78] proposed an SDN based cloud to provide safe data transmission with QoS. In order to deal with non-patchable vulnerabilities, Ge et al. [79] proposed to change the attack surface of the IoT network in order to increase the attack effort by using SDN. In [80] block chain technology is used to create secure virtual zones where things can identify and trust each other. Self-organization Blockchain Structures (BCS) are designed to establish the relationship between blockchain and IoT, as proposed in [81]. Ra et al., in [82], use block chain technology to provide confidentiality in a smart home environment. Table 11 presents other methods or technologies used currently for IoT security, which includes physical layer security.

#### 5. Discussion

This survey intended to give an overview of the current trends in IoT security research. At the same time, this survey presented some attack vectors and challenges to IoT security. High quality papers from Web of Knowledge were reviewed and categorized into by their objectives, methods used in the research, and the simulation tools used in order to simulate or validate the results. It was found that other than the simulation tools and modeller, the availability of the platform to validate the security protocol will help in producing a novel IoT security protocol. Hence, there is no doubt that the rapid progress of research in IoT security is supported by the availability of simulation tools and IoT modellers.

There have been real catastrophic events resulting from attackers using insecure devices as “thingbots” to attack the IoT network. This is strong evidence that the security of the IoT is of pressing concern. It is also assumed that the IoT will remain a target and attack vector for years to come. This is due to the increasing number of IoT devices, the heterogeneity of the protocols used in the IoT, and the minimal or default security measures embedded in the devices by the manufacturers. Clearly, cyber (IT) security, such as authentication, encryption, and firewalls, should be implemented as security measures in the IoT. But this is not sufficient. The interaction and integration between physical and cyber systems make the IoT different from the traditional network.

New vulnerabilities, such as unsecured communication channels, the presence of malicious activities in the network, and unsecured physical devices, introduce new type of threats to the IoT networks. This also evidences that IoT devices are the targets of surface attacks due to their irregular patching and updates: often the devices come with minimal or maybe no authentication or encryption at all. Furthermore, usually these devices are deployed in a hostile environment and available at all times; hence there may be minimal or no protection against any illegal physical access.

**Table 11**

Other methods which are used in the recent research.

| Ref  | Layer       | Objective                     | Method                                | Domain     | Simulator/Computation/Analysis tools |
|------|-------------|-------------------------------|---------------------------------------|------------|--------------------------------------|
| [83] | Network     | Maximum security pay offs     | Game theory                           | Generic    | Not available                        |
| [84] | Network     | Lightweight anomaly detection | Game theory                           | Generic    | Not available                        |
| [85] | Network     | To detect DoS                 | Game theory                           | WSN        | NS2                                  |
| [86] | Network     | Secure communication          | TCP/IP based comm.                    | Generic    | Testbed                              |
| [87] | Network     | Privacy                       | Location privacy algorithm            | Generic    | Not available                        |
| [88] | Network     | Anomaly detection             | Network scanning                      | Generic    | NS3, MATLAB                          |
| [89] | Network     | GPS spoofing                  | Hybrid localization                   | Drones     | Open CV                              |
| [90] | Network     | Anomaly detection             | HIST and Game theory                  | Generic    | TOSSIM and AVRORA                    |
| [91] | Network     | Data integrity                | Linear network coding                 | Generic    | MATLAB                               |
| [92] | Physical    | Location spoofing             | Geo-spatial tagging algorithm         | Generic    | Testbed                              |
| [35] | Physical    | Security tagging              | System hardening                      | Generic    | Prototype                            |
| [93] | Multi layer | Security analysis             | Mathematical modelling                | Generic    | No                                   |
| [94] | Network     | Secure communication          | Enhancing MQTT                        | Generic    | Testbed                              |
| [95] | Network     | Malicious node detection      | Mathematical algorithm                | Industrial | OMNet, MATLAB                        |
| [96] | Physical    | Mitigate eavesdropper         | Physical layer security               | Generic    | C++                                  |
| [97] | Physical    | Securing uplink transmission  | UOSPR lightweight single antenna      | Generic    | NS3, MATLAB                          |
| [98] | Physical    | Secure transmission           | Cooperative jamming                   | Generic    | MATLAB                               |
| [99] | Network     | IDS                           | Heterogeneous access control protocol | Generic    | Not available                        |

Authentication and encryption may be effective solutions in mitigating security issues in IoT. However, for low-power, computationally and resource constrained devices, the implementation of effective authentication and encryption is still in its infancy and does not guarantee the prevention of malicious nodes in the network, such as corrupted devices or machines. Furthermore, due to its convenience, manufacturers usually apply hardcoded credentials or passwords, something which typically leads to a significant authentication failure. From this survey, it is seen that current research on devices' security has mainly focused on improving lightweight authentication and encryption for low-power and resource constrained devices.

On the other hand, securing the routing protocol at the network layer and implementing trust and reputation based malicious node detection suffers end-to-end delay, communication overhead, and a high false positive rate.

The findings from this survey demonstrate that even though authentication alone may not be sufficient for IoT security, the current trend of IoT security mechanisms is to work on lightweight, mutual and multi-factor authentication, especially at the network and application layers. On the other hand, in order to mitigate devices' security issues, lightweight and low cost encryption are proposed for the physical layer.

In conclusion, according to the IoT security architecture, security mitigation encompasses all the layers in the basic IoT architecture, namely, perception, network, and application, even though it is observed that most of the current mechanisms are applied to the network layer. It also can be concluded that an appropriate IoT threat modelling might be useful in strategizing effective IoT security mitigation.

## 6. Conclusion

The purpose of this survey has been accomplished by giving an adequate overview of the research trends in IoT security between 2016 until 2018 and the relevant tools and simulators. The research from reputable publishers have been reviewed and categorized for easy reference for new researchers. Future directions of this research include developing a comprehensive IoT threat modelling, followed by designing a zero trust algorithm to mitigate known and unknown cyber-attacks on an IoT system.

## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:[10.1016/j.comnet.2018.11.025](https://doi.org/10.1016/j.comnet.2018.11.025).

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