UNIVERSITY OF TARTU
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Shapaval Raman

Security Risk Management for the IoT systems

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Supervisor: Raimundas Matulevicius, PhD

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Abstract:

Since 2012 the number of units in global infrastructure for the information society (The Internet of Things) has grown twice. With this number also has grown the number of possible threats and risks, which influence security on all levels of the system. As a result, a huge amount of users' data was stolen or damaged. According to Third Quarter, 2016 State of the Internet / Security Report based on data gathered from the Akamai Intelligent Platform the total number of DDoS attacks in Q3 2016 increased in 71% compared to Q3 2015. With 623 Gbps data transfer attack it was largest DDoS ever and this fact will only increase the number of future attack events. All these facts reveal a problem that a lot of IoT systems are still unsecured and users' data or personal information stay vulnerable to threats. The thesis combines knowledge of Security Risk Management with existing practice in securing in IoT into a framework, which aim is to cover vulnerabilities in IoT systems in order to protect users' data. We propose an initial comprehensive reference model to management security risks to the information and data assets managed and controlled in the IoT systems. Based on the domain model for the information systems security risk management, we explore how the vulnerabilities and their countermeasures defined in the open Web application security project could be considered in the IoT context. To illustrate the applicability of the reference model we test the framework on self-developed IoT system represented by Raspberry Pi 3 interconnected with sensors and remote data storage.

Keywords:

Internet of Things (IoT), Information Systems Security Risk Management (ISSRM), Open Web Application Security Project (OWASP)

CERCS: P170 Computer science, numerical analysis, systems, control

estonian

IoT-süsteemide turvalisuse riskijuhtimine

Lühikokkuvõte:

Alates 2012.aastast ülemaailma infastruktuuri üksuste arv (The Internet of Things) on jõudsalt kasvanud üle kahe korra. Selle numbriga on ka kasvanud võimalikud riskid ning ohud, mis mõjutavad süsteemi turvalisust. Tulemuseks suur hulk isiklikute andmetest on varastatud või kahjustatud. Vastavalt «Third Quarter, 2016 State of the Internet / Security Report» ning põhinedes « Akamai Intelligent Platform» DdoS rünnakute arv, Q3 2016 suurenes 71%-ni võrreldes Q3 2015. 623Gbps rünnak oli kõige suurim DdoS rünnakutest, mis oli kunagi fikseeritud. Kõik need faktid tõestavad, et Iot süsteemis on veel siiamaani probleemid isikuandmete turvalisusega. Isklikud andmed on ohtude suhtes haavatavad. Käesoleva töö ühendab teadmised turvalisuse riskijuhtimine olemasoleva praktikaga Iot raamastikus. Raamastiku eesmärk on tugevdada nõrgad osad Iot süssteemis ning kaitsta isiklikuid andmeid. Pakume esialgse igakülgse võrdlusmudeli juhtkontrolli turvariskideks IoT süsteemides hallatavate ja kontrollitavate info- ja andmevarade puhul. Infosüsteemide turvalisuse riskijuhtimise valdkonna domeeni mudeli põhjal uurime, kuidas avatud veebirakenduse turvalisuse projektis määratletud turvaauke ja nende vastumeetmeid võiks kaaluda IoT kontekstis. Selleks, et illustreerida etalonmudeli rakendamisest, raamastiku katsetatakse IoT-süsteemil. Selle süsteemi kuuluvad Raspberry Pi 3, sensorid ning kaugandmete ladustamine.

Võtmesõnad: Internet of Things (IoT), Infosüsteemide Turvalisuse Riskijuhtimine (ISSRM), Open Web Application Security Project (OWASP)

CERCS: P170 Arvutiteadus, arvutusmeetodid, süsteemid, juhtimine (automaatjuhtimisteooria)

Contents

1 Introduction

Internet of Things (IoT) is a network of connected devices and systems to exchange or accumulate data and information generated by users of embedded sensors in the physical objects [4]. Among the privacy, energy-awareness, environment, and other concerns, security plays an important role, as the (potentially sensitive) data is sent among the various devices and multiple users. In cases where such a data is intercepted and used for non-intended purposes, it may lead to the severe damages of the valuable system and/or environmental assets [7] [59] [60] [61] [62] [63]. There exist a number of surveys related to the IoT security [9] [10], security of the IoT frameworks [24] [26], or specific components of the IoT systems [14] [15] [19]. In this paper, we propose a comprehensive reference model for the security risk management in the IoT systems. We base our proposal on the domain model for the information systems security risk management (ISSRM) [21] [1] – thus, we focus on the security risks to the information and data managed in the IoT system. Since the IoT systems much depend on the cloud and Internet computing we consider how vulnerabilities and their countermeasure considered in the open Web application security project (OWASP) [45] can help when identifying and managing the security risks in the IoT systems. To apply existing solutions in securing Web application to the IoT system we propose self-developed IoT Security Reference Model built on top of IoT and SRM domain models.

The rest of the paper is structured as follows: Sect. 2 studies the previous work in securing IoT and determines its taxonomy which is then illustrated as IoT Reference Model. In Sect. 3 we overview the Security Risk Management as a development process along with the ISSRM domain model. Sect. 4 based on the IoT domain model presents components for managing IoT security risks. This includes discussion on the IoT assets, their vulnerabilities, and countermeasures used to mitigate these vulnerabilities. Sect. 5 gives few examples illustrating some reported security risks. Sect. 6 represents an application of the developed framework to the real-word IoT system and test results. Finally, Sect. 7 concludes the paper and provides directions for future work.

2 Related Work

This chapter surveys previous work in the Internet of Things security. These days the Internet of Things (IoT) popularity, as a research topic, is growing rapidly because of its interconnected components heterogeneity and the availability to communicate without human intervention [5]. The fact that IoT is heavily affecting our lives in different domains, from wearable devices such as smartwatches or fitness trackers till huge manufacturing systems, forced the rapid growth in IoT-based application development and consequently the need of appropriate IoT frameworks [6]. However, most IoT devices are easy to hack and compromise due to its hardware limitations of computing power along with lack of storage and network quantity [12]. Therefore, security and the ability to monitor IoT system state, along with the study of recent attacks on this sector became a ground vector in developing frameworks for securing IoT systems.

2.1 Taxonomy of the IoT

According to [13] IoT can be classified into four domains: 1) Perception Domain; 2) Access Domain; 3) Network Domain; 4) Application Domain. The general structure is presented on Figure 1.

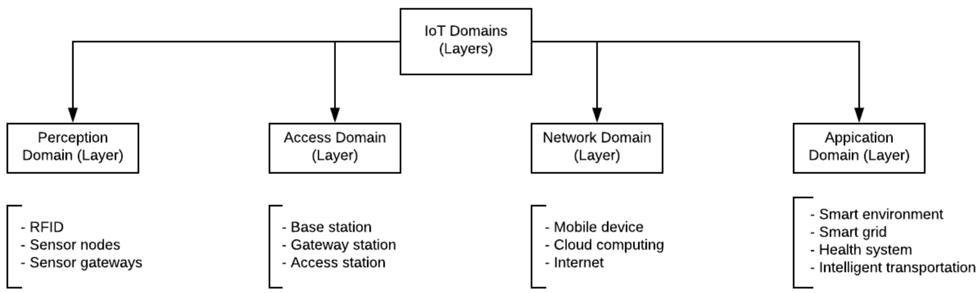


Figure 1. IoT Domains (Layers).

2.1.1 Perception Domain

Current domain collects information using readers or gateway. This domain can be divided into two sections: (i) *perception node*, which is represented by sensors, controllers etc; (ii) *perception network*, which aim is to interconnect the network domain. Actual reader can extract information from the message received from the RFID tag, which is sticked to the 'thing', while gateway read signals from the sensors, consequently determining the existence of the 'thing' or changes in the environment [13] [5].

RFID can be presented as a revolution technology in the embedded communication model, which provides functionality for microprocessors' wireless communication configuration. There are two types of RFID: (i) *active* - RFID tags with their own power source, which provide signals to readers, creating instant communication; (ii) *passive* - tiny RFID tags with unique identity to support active communication between tags and readers using wireless networks [13].

Sensor nodes take care of gathering and processing of the sensed data, while being interconnected with other nodes in the network. They have next components: (i) *controller* - takes care of data processing and other node's parts performance; (ii) *transceiver* - transmits and receives radio frequencies; (iii) *program memory* - is used for programming device; (iv) *power source* - supplies node with power; (v) *hardware* - senses data from the environment. Sensor itself and actuator can be described as the major one components, as they sense data and activate/deactivate device based on commands from the nodes [13].

If we look at the wireless networks and how the data is collected from various WSN nodes, we will come to the sensor gateways, which provide the above-mentioned functionality. Each gateway supports 2.4 GHz IEEE 802.15.4 radio and with a communication framework on board it checks and records the conditions of various sensors. Transmitters and receivers create radio channels between two or more devices to provide data-exchange functionality [13].

2.1.2 Access Domain

In the access domain, the reader or the head of gateway transfers sensed data to the access point, which is represented by the gateway or base station. The access point then transfers data to the network domain [5].

2.1.3 Network Domain

Mobile devices can be characterized as a portable device with its own operating system on board, which supports inbuilt or external applications. These devices are usually equipped with such technologies as Wi-Fi, Bluetooth, Near-Field Communication (NFC), Global Positioning System (GPS) etc. Mobile devices connected to the Internet can provide users with nearly unlimited functionality in a digital word. However, they also produce a branch of vulnerabilities, which result in an uncounted number of threats to all users' personal data.

Clouds or cloud computing are Internet-based services, which consist of hardware, systems software, and applications and provides users with resources on-demand. There are three main cloud categories: (i) *Software as a Service* (SaaS) - user can use an application on-demand, but can not control hardware or network. Such model provide users with applications through the network; (ii) *Platform as a Service* (PaaS) - allows user to host environment for their applications, however the operating system, hardware or network infrastructure still can not be controlled; (iii) *Infrastructure as a Service* (IaaS) - gives user an access to ‘fundamental computing resources’ such as CPU, memory, middleware and storage, but cloud infrastructure remains protected [22].

" The Internet is the global system of interconnected computer networks that use the Internet protocol suite (TCP/IP) to link devices worldwide. It is a network of networks that consists of private, public, academic, business, and government networks of local to global scope, linked by a broad array of electronic, wireless, and optical networking technologies. The Internet carries a vast range of information resources and services, such as the inter-linked hypertext documents and applications of the World Wide Web (WWW), electronic mail, telephony, and file sharing " [56].

2.1.4 Application Domain

The last domain, but not the least, is the application domain, which can implement the logic in interconnection between ‘things’ and ‘things’ or between ‘things’ and person and plays crucial role in the whole IoT structure as a head part, which is visible to user and wrap all functionality into User Interface (UI) [5] [13]. We can allocate four ground types of applications which represent this domain: (i) *Smart environment* - is represented by intuitively operated devices that help us to organize, structure, and master our everyday life. In other words, smart environments provide functionality, which helps the human to interact with surroundings and reach his goals [27]; (ii) *Smart grid* - an intelligent power supply network, which provides communication functionality based on two-way wireless and/or wireline communication technologies. The main aim is to increase the productivity and efficiency of the networks. National Institute of Science and Technology (NIST) considers mobile broadband technologies such as 2G/3G/4G as key enablers for Smart Grid networks, while Electric Power Research Institute (EPRI) examines technologies such as Mobile WiMAX, GPRS, and LTE as key enablers for automated metering infrastructure (AMI) [37]; (iii) *Healthcare system* - is a framework based on radio frequency technology to deliver sensed data from fragile and accurate micro-nodes embedded inside or outside humans body; (iv) *Intelligent transportation systems (ITS)* - represents a stack of high technology and improvements in information systems, communication, sensors, and advanced mathematical methods interconnected with the surface transportation infrastructure [28].

Each application should be mindful, active and personalized in order to provide secure and stable communication between devices.

2.2 Taxonomy of the IoT Security

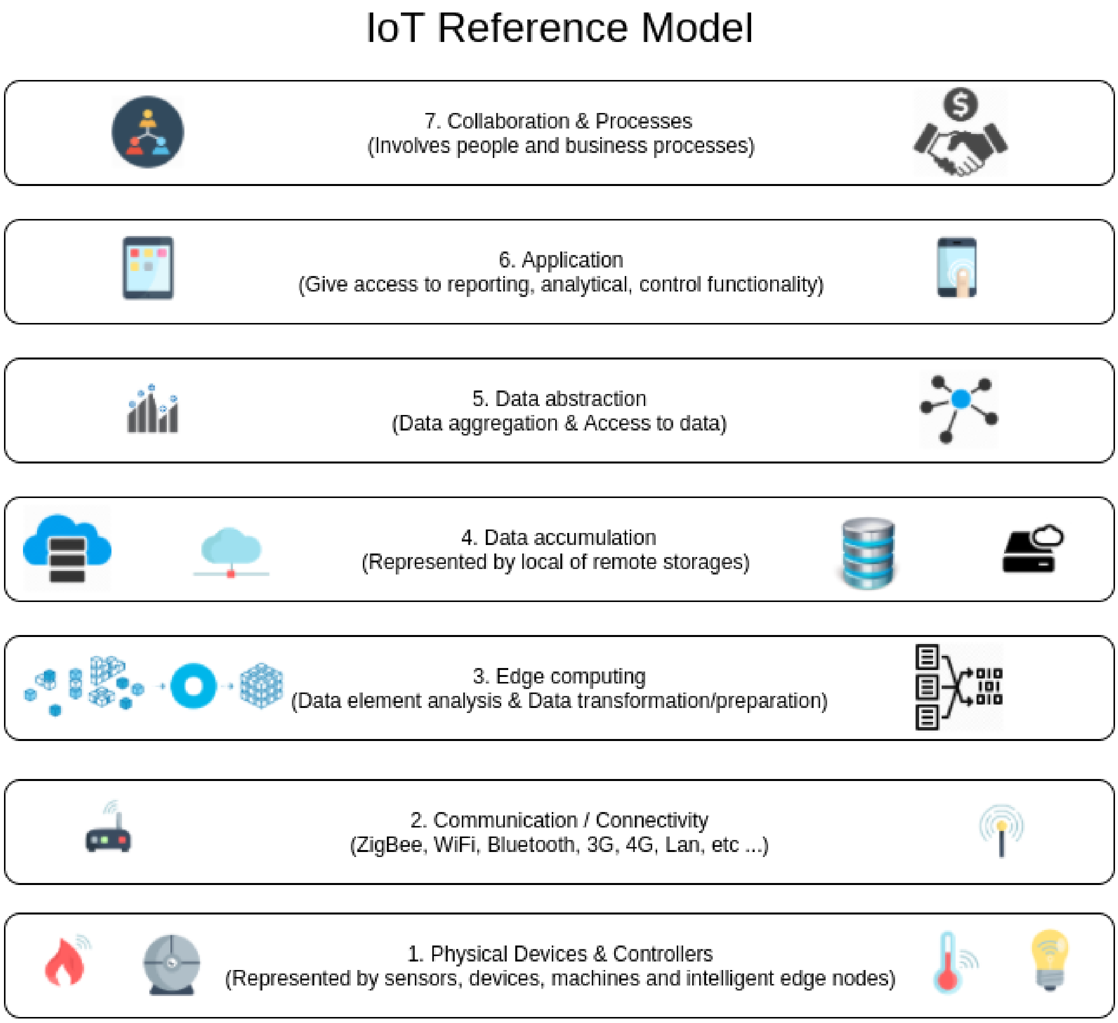


Figure 2. IoT Reference Model.

Before aiming at IoT security taxonomy we should study the IoT Reference model. If we look at Figure 2 we can see that based on section 2.1 we can precisely allocate seven general IoT system layers. *Physical devices & Controllers* along with *Communication/-Connectivity* represent instances of the *Perception* and *Access Domains*, which role is to sense data and transfer it to the *Network Domain*. Sensed data goes through *Edge computing, Data accumulation* and *Data abstraction* layers. During *Edge computing* data can be analyzed and appropriate transformation/preparation can be done before consequent storing. Next step in *Network Domain* is *Data accumulation*, which is responsible for storing sensed and computed data locally using in-system resources or remotely if additional computing power is a need. One more instance of the *Access Domain* is represented by *Data abstraction* layer, which aggregates data from storage and provides access to it. *Application Domain* itself play a role of a layer in IoT Reference Model, in general, it gives access to reporting, analytical and control functionality of the IoT system. Finally, *Collaboration & Processes* layer involves people and business processes as actors in the IoT system.

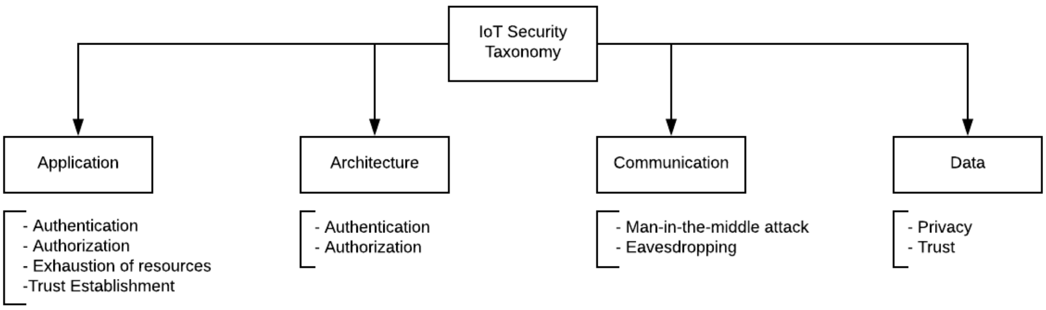


Figure 3. IoT Security Taxonomy.

The existing IoT classification is definitely complicated and heterogeneous, that is why we need to investigate the actual IoT security taxonomy which should be simple and more specifically aimed at characterizing classes of security threats and vulnerabilities in each IoT layer. After studying a branch of existing IoT frameworks [8] [17] [35] [30] [16] we can allocate four main classes in IoT security, see Figure 3: (i) *Application domain* - consists of security techniques such as authentication, authorization, exhaustion of resources, trust establishment etc; (ii) *Architectural domain* - always depends on the scenarios and application domain. According to [5] [8] [17] [35] [30] [16] we can provide a summery of existing IoT architectures, see Table 1; (iii) *Communication* - responsible for information exchange/sharing between IoT devices in the system through its layers or between different IoT systems; (iv) *Data* - one of the main targets for threats, its privacy must be guaranteed.

Table 1. Examples of existing IoT architectures

Architecture	Application Domain	Purpose
SDN Architecture	Smart environment	SDN manages the network state and the resource allocation influences the whole system through centralization of the network controller. SDN produces the computing results for an optimized network status [8].
NFV Architecture	Smart environment	NFV network functions are implemented with the usage of servers and storage devices of industry standard, which can also be represented by virtual machines. With the reduction of the number of hardware appliances and the establishment of the high volume hardware usage, NFV contributes efficiency and flexibility to the system [8].
SEA Architecture	Healthcare	SEA: A Secure and Efficient Authentication and Authorization. SEA accomplishes authentication and authorization of remote end-users using smart e-health gateways. Being relied on the certificate-based DTLS handshake SEA provides a secure solution for the medical sensors [17].
Smart City Architecture	Smart City	The main aim is to combine business architecture, information system architecture and technology architecture into meta-model, which supports consistency, completeness, traceability, and a relationship of components and layers in the enterprise architecture of the smart city [35].

Service-Oriented Architecture (SOA)	Smart transportation	SOA defines secure IoT middleware architecture services, which aggregate data streams within the network in order to reduce the overall network load. Although, such architecture enables the interconnection of system elements with different interaction styles. "IoT-based SOA holds the promise of easing the development of rich applications integrating the physical with the virtual worlds in a multitude of domains" [30].
OSCAR: Object Security Architecture	Smart grid	Introduces modern scalable and efficient architecture for E2E security and access control in IoT along with architecture evaluating in M2M settings.
Conceptual Organizations Framework	Business organizations	Conceptual Organizations framework " adopts a broad perspective based on User Experience design and attempts to bridge design and system engineering constructs with cognitive and socio-cultural theories, in order to provide a common understanding to multi-disciplinary IoT development teams" [16].

2.2.1 Security Challenges in Application layer

Major security challenges in the Application layer can be presented by next groups [5]:

(i) *Authentication* - allows integration of different IoT devices from different context. During the authentication process, it is required to authenticate routing peers used for data transferring/exchanging along with origin data node authentication. Consequently, we can affirm that key deployment and key management are ground challenges in IoT authentication [12]. Authentication of nodes is always necessary for a good and secure implementation as it provides prevention against illegal node access. Authenticating the end to end communication makes the communication secure and the attacker will not be able to spoof the messages between those end hosts. One more challenge is to maintain authentication schemes both lightweight and reliable [29].

(ii) *Authorization* - addresses the security issue of illegal node access by specifying the access rights to different resources. The data should always be securely protected and accessible only to authorized users. As each IoT node supports limited techniques for access verification it is always challenging to provide appropriate authorization mechanism which will be beneficial and tolerate to nodes with different capabilities [23].

(iii) *Exhaustion of resources* - one of the challenges resulted from attacks, which aim is to drain the energy of the target IoT node through routing loops or extending packets transferring paths. Each node can be physically attacked and compromised, consequently, it can be used to perform malicious activities inside the network. Therefore, the main challenge occurs when one of the nodes is compromised and as a result, the cryptographic techniques are no more useful as the attacker got an access to the keys and encryption schemes through compromised node [29].

(iv) *Trust establishment* - an important aspect of each IoT system because such systems often deal with sensitive data. They store, transfer, recurrently process retrieve, and take decisions upon this type of data. In such cases, enforcing trust supposes to be a key feature of the functional behavior of all elements, protocols, mechanisms, and entities of the IoT system. Providing a trust model on application-level in order to follow the guidelines of data integrity and confidentiality establish a ground challenge for sensitive data security [2].

2.2.2 Security Challenges in Architecture

Building an architecture which tackles various security problems in IoT environment was never a trivial procedure. Any IoT architecture should not only address security issues from the Application layer (Sec. 2.2.1) but also take care of possible challenges that can be faced while deploying IoT devices over Software Defined Networks (SDN) and different clouds services [12]. Consequently, a branch of security issues of SDN and cloud environment would be inherited to underlying IoT system. Have also be mentioned that complexities, which involved in secure communication between object-oriented IoT networks and data-oriented cloud services, would produce even more extraordinary security challenges [11]. Networks' traffic monitoring for malicious data and unwanted actors represents one more challenge in IoT architecture, which is very demand for modern intrusion detection and unwanted connections prevention systems.

2.2.3 Security Challenges in Communication

The communication can be described as a process of exchanging/sharing data among the IoT devices or between different IoT layers/systems. With the enormous heterogeneity of the IoT systems, the entire communication infrastructure always wide and vulnerable to privacy loss. Main challenges in these domain connected to possible attacks, which can be described as follows [5]:

(i) *Meet-in-the-Middle Attack* (MitM) - " is a classical technique of cryptanalysis which applies to many constructions. The idea is that the attacker constructs patterns that propagate from both ends to the middle of the cipher, in some cases by partial key-guessing. If the events do not match in the middle, the key-guess was wrong and may be discarded. Such attack has been applied to 7-round DES (see the Data Encryption Standard) and to structural cryptanalysis of multiple-encryption (for example, two-key triple encryption. A recent miss-in-the-middle attack may also be seen as a variant of this technique in which the events in the middle should not match, and the keys that suggest a match in the middle are filtered as wrong keys" [33].

(ii) *Sieve-in-the-Middle Attack* (SitM) - consider to be an improved version of MitM attack. [34] represents SitM as a new generic improvement of MitM algorithms, which allows attacking a higher number of rounds. They propose to compute input and output bits of particular middle sbox *S* instead of looking for collisions. Then the margin step is performed and all key candidates, which do not correspond to a valid transition through *S* are discarded. Consequently, such technique allows performing more attacks on the target that classical MitM since it attacking sbox *S*. Moreover paper introduces technique on how to avoid an increase in data complexity while combining SitM with bicliques if the key size of the cipher is larger than its block size [34].

(iii) *Eavesdropping* - is intercepting and logging of the information between two interconnected nodes. It always occurs on the network layer in the IoT and represents a form of data sniffing [5]. Despite the fact that such technique can be used to facilitate the troubleshooting or performance tuning of the IoT system, attacks based on eavesdropping can provide insight into the application design and communication principles for the unwanted actors (attackers).

2.2.4 Security Challenges in Data protection

If we look at the taxonomy of IoT systems, it is very important to know how to support end-to-end data security and privacy. We should always be ensured of authenticity, integrity, and confidentiality of the data collected from or transferred through heterogeneous IoT devices. Security solutions should not implement just existing cryptosystems and protocols, it's more efficient to develop a set of cryptographic primitives and protocols, which always data-driven, IoT context-aware, lightweight, mission-critical, energy-saving, and service-oriented [20].

According to the working party on the protection of individuals with regard to the processing of the personal data and based on Opinion 8/2014 on the on Recent Developments on the Internet of Things we can determine next privacy and data protection challenges related to the Internet of Things (article 29 Data Protection working party) [25]:

1. *Lack of control and information asymmetry*

   As a result of the need to provide heterogeneous services to the every-day growing number of IoT users, the usage of the third-party monitoring systems becomes more and more popular. Such a trend can lead to situations where a user can lose all control over his private data, depending on whether or not the collection and processing of this data will be made in a transparent manner or not.

   In other words, an interaction between IoT systems' actors, devices and components can result in the accumulation of the big amount of data, which can hardly be managed and protected. Consequently, if the data can not be controlled even in the generation and accumulation stages, there are no options to guarantee appropriate control of the data flow in the system. " This issue of lack of control, which also concerns other technical developments like cloud computing or big data, is even more challenging when one thinks that these different emerging technologies can be used in combination ".

2. *Quality of the user's consent*

   In many cases, data processing operations could be covered by the user, which influence the transparency of the personal data for the owner. " In such circumstances, consent cannot be relied upon as a legal basis for the corresponding data processing under EU law ". Wearable devices such as smartwatches are also not noticeable, as they can collect and distribute users' personal info by using embedded sensors without actual user participation. Consequently, to avoid such cases ("the identification of data processing through Wearable Computing") we should introduce some notification (logging) functionality to be sure that user at least is notified about actual personal data flow directions. However, it is clear that classical mechanisms used to obtain individuals' consent may be difficult to apply in the modern IoT systems, this fact leads to "low-quality" consent provided due to the fact that such 'things' as sensors are usually designed neither to provide information by themselves nor to provide a valid mechanism for getting the individual's consent. That is why new consent mechanism should be provided, which will be implemented through IoT devices itself.

3. *Inferences derived from data and repurposing of original processing*

   Daily the amount of the data generated by the IoT systems is strictly increasing, consequently, such data could be lent to secondary uses while being analyzed, transformed or preprocessed. " Third parties requesting access to data collected by other parties may thus want to make use of this data for totally different purposes " [25]. Moreover, the vectors of data analysis cannot be strictly limited, for example, at first glance insignificant data collected from an accelerometer and the gyroscope of a smartphone can be used both for some routing application or to determine the individual's driving habit. Such fact cannot be neglected and the risk analysis techniques should be applied while development IoT system's sensors tree. The issue is that the user can be comforting to share his private data to obtain only specified service and may not want this information to be used for different purposes and analyzed in another way that is needed for providing current service."Therefore it is important that, at each level (whether raw, extracted or displayed data), IoT stakeholders make sure that the data is used for purposes that are all compatible with the original purpose of the processing and that these purposes are known to the user " [25].

4. *Intrusive bringing out of behavior patterns and profiling*

   Despite the fact that data could be collected by separate isolated pieces of information, it still could be analyzed and specific aspects of an individual's habits could be revealed. But generating such knowledge from users' data could lead to extraction of the even more detailed and complete life and behavior patterns of the user. If the IoT system would not be able to guarantee the privacy of users behavior or prevent detection of the hidden patterns this will put a pressure on the individual. "Such a trend would be very intrusive on the private life and the intimacy of individuals and should be very closely monitored " [25].

In this section we have discovered the heterogeneity of IoT along with its main security challenges. Based on related work we have provided IoT Reference Model (Figure 2.) and it is now clear that in the IoT scenario, security solutions cannot be limited to the single layer, it always has to be an end-to-end combination of overcoming challenges for each class in IoT taxonomy. Consequently, we have to understand the possible issues in each layer in detail as the heterogeneity of IoT interacting objects makes it impossible to construct a solution from outside the system, we have to go from inside, combining solutions from different security levels into one strong consequent flow of countermeasures.

3 Security Risk Management

In general, Security Risk Management (SRM) can be described as a part of the secure systems development process, which aim is to understand what assets should be protected, from which risks and how these risks could be allayed while covering discovered vulnerabilities of the system [1]. SRM plays a leading role in developing appropriate solutions based on the situation and existing security countermeasures. Typically it provides a set of rules to lower the risk level or totally prevent possible attacks on the system along with the hints for successfully and qualitative system monitoring. There are many different methodologies which apply SRM in various domains, that's why a deep understanding of the system's architecture is crucial during SRM analytical procedure.

3.1 Introduction to Security Risk Management

According to [1] we will look at a few of SRM methods as the number of existing approaches always grow and we can not pretend our survey to be complete. However, chosen SRM methods should be enough to understand what kind of analysis concepts and principles are used during an analytical procedure in security risk management.

CORAS is a risk assessment methodology [40] which provides detailed instructions for the use of UML-oriented modelling for the next three main purposes: (i) "to describe the target of assessment at the right level of abstraction" [40]. (ii) "as a medium for communication and interaction between different groups of stakeholders involved in risk assessment" [40]. (iii) "to document risk assessment results and the assumptions on which these results depend" [40]. There are three ground steps for the risk analysis of the *CORAS* risk management process: (i) identify risks; (ii) analyse risks; (iii) evaluate risks. The *CORAS* risk management process based on using a branch of approaches in terms of XML technology for analyzing different parts of the system independently. The choice of the method is made by evaluating the viewpoint in which the part to be analyzed appears and determining development lifecycle phase.

EBIOS (French: Expression des Besoinset Identification des Objectifs de Securite) is a method for analyzing, evaluating and counter-measuring against risks in the system. There are five main steps of the *EBIOS* method [41]: (i) Circumstantial study - determining the context; (ii) Security requirements; (iii) Risk valuation; (iv) Security goals determination; (v) Identification of security requirements. According to [41] *EBIOS* generates a security policy adapted to the system based on its specifications and features. The method was created in 1995 and is now maintained by the ANSSI, a department of the French Prime Minister.

AURUM (Automated Risk and Utility Management) is a framework for information security risk management [42], which was developed to help in decision making according to organizational needs with respect to the selection of security measures. It represents a new methodology for supporting the NIST SP 800-30 risk management standard. According to [42] the next benefits were documented: (i) *AURUM* provides risk manager with an "ontological information security knowledge base" in order to structure the information security knowledge in appropriate way; (ii) Describes the methodology for the consistent modelling of organizational resources; (iii) Provides guidelines for using "widely accepted information security knowledge for threat/vulnerability identification and control recommendations" [42]; (iv) Introduces usage of the Bayesian threat likelihood determination, which gives opportunity for the objective level threat evaluation; (v) Automated threat impacts calculation as a part of system's resources rating; (vi) Automated controls proposals for the risks mitigation; (vii) Provides risk manager with an opportunity to investigate possible scenarios and characterize the problem in details;

MEHARI (MEthod for Harmonized Analysis of RIsk) is a free risk management method for the information systems. This framework combines a complex knowledge base with existing tools into the powerful instrument for the information security risk analysis [43]. There are next ground steps: (i) Threat analysis; (ii) Business process analysis; (iii) System assets classification; (iv) Risks ratio processing; (v) Diagnostic questionnaires for evaluation risks' mitigation level of the system; (vi) System Security Requirements evaluation; (vii) Possible scenarios determination; (viii) Developing countermeasures based on possible risks scenarios; Entire focusing on the risks analysing and creating controls makes *MEHARI* a powerful framework for the SRM.

CRAMM (CCTA Risk Analysis and Management Method) is an automated tool based on qualitative risk assessment methodology, which consists of the next stages [44]: (i) Assets identification and evaluation; (ii) Threat and vulnerability assessment; (iii) Countermeasures recommendation; As it mentioned in [44] "CRAMM is a comprehensive and flexible tool especially for justifying prioritized countermeasures at a managerial level, needing, however, qualified and experienced practitioners for efficient results".

3.2 Domain Model for SRM

One of the most important roles in Security Risk Management (SRM) is played by the SRM Domain Model. The main purpose of a domain model is to represent the main concepts of the system with their responsibilities and relationships. Based on the main features of the concepts, we can then classify them as different assets [2]. In this way, we can determine what assets need to be protected and from which risks. Such strategy helps to generalize understanding of the system's problem between people who are working on possible solutions for it. Only with a common understanding of the main concepts, it becomes possible to argue about architectural solutions and to evaluate them.

We have SRM domain model (SRMDM) represented as a UML diagram in Figure 1. All elements of the SRMDM could be divided into three major groups [1]: (i) *asset-related concepts* - "describe which of an organization's assets are important to protect and what criteria guarantee a certain level of asset security" [1]. Typically pure *asset* can be represented by any part of the system which has some value and plays a role in the work of the whole system. Assets can also be divided into sub-groups: *business assets* ("describes the information, processes, capabilities and skills essential to the business and its core mission" [1]) and *organizational assets*, which are represented by the core elements of the system and play a crucial role in providing appropriate service to the customers; (ii) *risk-related concepts* - "introduce definitions of risk itself and its immediate components" [1]. According to the Figure 1 we can allocate *risk* itself as a combination of the *threat* which exploits existing *vulnerability* of the system plus *impact* to which such *event* can lead to.; (iii) *risk treatment-related concepts* - "describe the concepts to treat risk" [1]. According to [1] we can choose one of four ground risk treatment decisions while risk mitigating process: *Risk avoidance* - describes approach of modifying system's functionality to fully avoid possible risk; *Risk reduction* - proposes strategy of the minimization risk occurrence possibility, so security requirements are, typically, selected for reducing the risks instead of full avoidance; *Risk transfer* - "defines how risk parties could share the burden of loss from a risk" [1]; *Risk retention* - "constitutes acceptance of the burden of loss from a risk. No design decision is necessary in this case." [1].

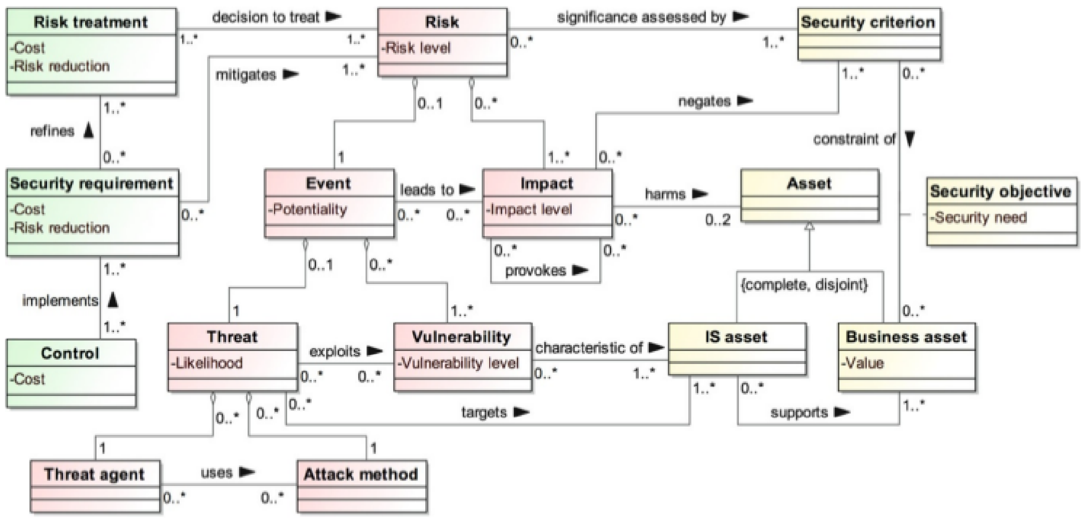


Figure 4. General SRM Domain Model.

4 Content and Assets of IoT

The Internet of things (IoT) is represented by wisely connected devices and systems to exchange or accumulate and process data generated by users or by embedded sensors and actuators in machines and other physical objects. IoT starts playing leading role in improving customers' life quality on different layers including security, health, education, and energy efficiency. Industrial business has also experienced advantages of using IoT systems in manufacturing, retail, agriculture and other sectors [38].

As the IoT through last years has gained a significant positive impact on consumers, enterprises, and society as a whole it also has brought in a stack of risks connected to beneficial services provided by IoT systems. That's why we need to understand a General Domain Model Architecture of the IoT (GDMA) [39] in order to establish the common grounding definition of IoT system assets and to describe their basic interactions and relationships with each other.

4.1 IoT Domain Model

Internet of Things Domain Model (IoTDM) plays a leading role in applying SRM methods to the IoT systems since it provides a definition of the main abstract concepts of the system. The Domain Model helps to determine system and business assets of the IoT system and then evaluate their importance in order to apply appropriate countermeasures against existing risks. "The main purpose of a domain model is to generate a common understanding of the target domain in question" [2].

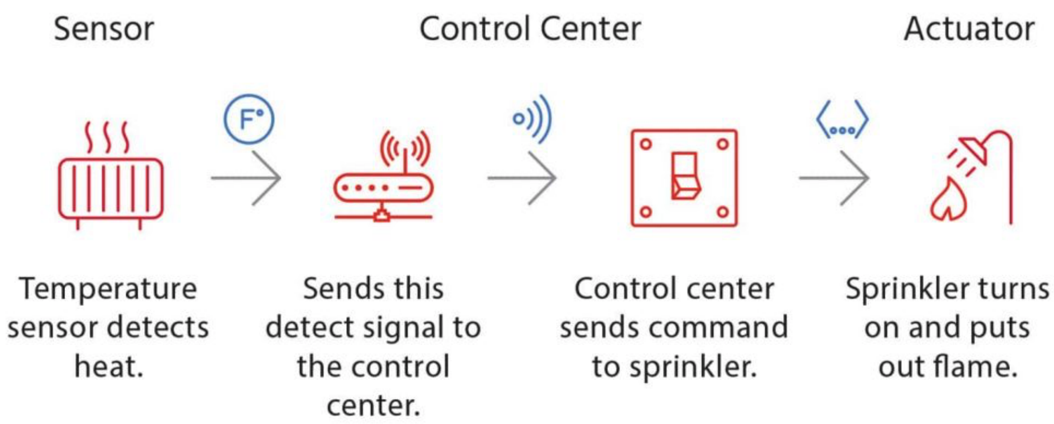


Figure 5. Sensor to Actuator work flow.

Figure 3 shows us a general IoTDM which we will use while applying SRM to the existing IoT system. However, before describing how we will secure real system and from which risks we have to describe our IoTDM in terms of SRM and determine relationships between concepts represented in both domain models.

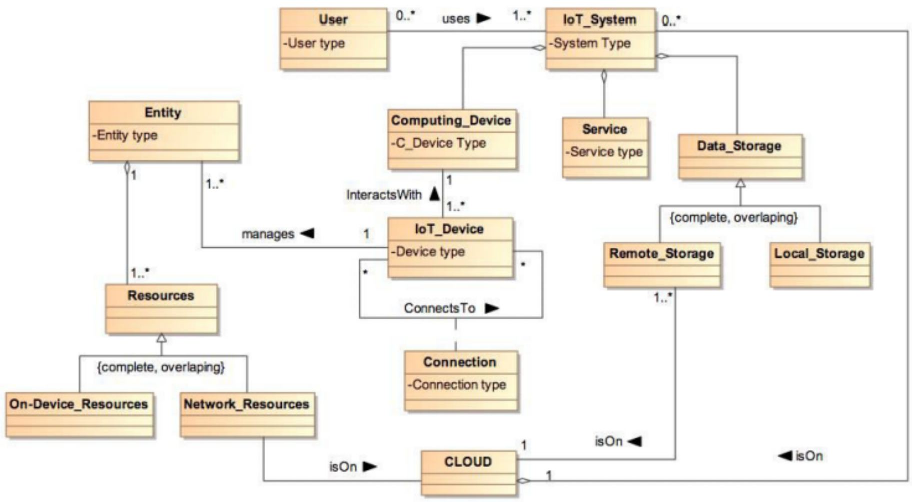


Figure 6. General Domain Model Architecture of the IoT.

Lets represent the initial work flow of the simple IoT system in terms of SRM. If we look at Figure 2 we can determine four IoT elements: (i) *temperature sensor* - detects heat; (ii) *Wi-Fi module* - sends detected temperature from the sensor to the *control center*; (iii) *control center* - makes decision what command should be sent to the sprinkler based on the previously received temperature from the *temperature sensor*; (iv) *actuator* - represented by sprinkler, turns on and puts out flame or turns off depending on the command from the *control center*. Suppose, an attacker, (*Threat agent*) with means to break a normal workflow of our IoT system from Figure 3, exploits the weakness of the Wi-Fi connection between Wi-Fi module and Control center, which represent *System assets*, and get an access to the temperature (*Business asset*) which is going from the sensor. Then an attacker changes the temperature value and this *Event* leads to the *Impact* of overheating and consequently to the *Harm* to the sprinkler. Such *Event* and its *Impact* represent *Risk* to the IoT system.

Finally, we can summarize that assets in the IoT represent anything that is valuable for the IoT system or play a crucial role in providing appropriate functionality and services to users. According to [1] *system assets* can be described as parts of the IoT system, which gain their importance through supporting business assets. Typically, system assets in IoT can be represented as ground components of the information technology system such as hardware, software or network. In our simple example from Figure 2 system assets are represented by the sensor, Wi-Fi module, Control center and Actuator.

Business assets are extremely valuable for each IoT system as they represent essential to the business things such as information, processes, capabilities and skills [1]. Besides official definitions, business assets can be commonly represented by the data, which is transferred, stored or manipulated by the IoT system during the working process. As a result business assets security is definitely worth attention. According to Figure 3 business assets are represented by the temperature which goes from the Sensor to the Control center and commands from the Control center to the Actuator.

4.2 Vulnerability

According to the cyber-security terms, we can determine vulnerability as a " term that refers to a flaw in a system that can leave it open to attack. A vulnerability may also refer to any type of weakness in a computer system itself, in a set of procedures, or in anything that leaves information security exposed to a threat " [57]. In terms of Security Risk Management applied to the IoT vulnerability is a characteristic of the system asset or group of IS assets that exposes a weakness or flaw in terms of security [1].

Have to be mentioned that if we talk about the vulnerability of the application, then it could be presented as a weakness in design flaw or an implementation bug, which can allow an attacker to harm application owner, application users, and other entities that rely on the application. According to the Open Web Application Security Project [45] we can allocate next most common IoT vulnerabilities:

1. **Insecure Web Interface, V#1:**
   Threat agent - an attacker with access to the web interface. Could be presented by the external or internal user of the system.
   Attack method - an attacker uses weak credentials, gains access to plain-text credentials or enumerates accounts to access the web interface.
   Vulnerability - account enumeration, lack of account lockout or weak credentials are the most common vulnerabilities of the insecure Web Interface.
   How to discover - issues of the Web Interface could be found out during manual work with the system along with using testing tools for cross-site scripting identification.
   Impact to system assets - insecure web interface could result in harm to service's data confidentiality, integrity, and availability which can then lead to complete device takeover.

Impact to business assets - the actual device or whole IoT System could be compromised along with the users.
Possible attack examples:

(i) The Forgot Password functionality provides responses on entering invalid users' credentials. As soon as valid credentials identified an attacker could calculate appropriate password using brood force methods.

(ii) Web interface maintains vulnerable to cross-site scripting. For example, the HTML snippet:

2. **Insufficient Authentication/Authorization, V#2:**
Threat agent - an attacker with access to the web interface. Could be presented by the external or internal user of the system.
Attack method - an attacker uses weak passwords, insecure password recovery mechanisms, poorly protected credentials or lack of granular access control to access a particular interface.
Vulnerability - weak passwords or credentials with poor protection can lead to insufficient authentication.
How to discover - common issues with authentication/authorization can be discovered while examining the interface of the system with automated testing and require more stable passwords.
Impact to system assets - insufficient authentication/authorization can result into harm to system's data confidentiality, integrity, and availability or denial of access.
Impact to business assets - all users could be compromised as a result of their data being stolen.
Possible attack examples:

(i) The interface requires simple passwords.

(ii) Users' credentials are not appropriate protected while transmission to the DB or not encrypted before sending.

3. **Insecure Network Services, V#3:**
Threat agent - an attacker with a network access to the IoT device. Could be an internal or external user.
Attack method - an attacker uses vulnerabilities in network services to launch an attack on the IoT device itself or bounce attacks off the device.
Vulnerability - not enough controls on open ports and traffic monitoring in the system.
How to discover - insecure network services can often be detected with the help of port scanners tools and fuzzers. " Fuzzing or fuzz testing is an automated software testing technique that involves providing invalid, unexpected, or random data as

inputs to a computer program. The program is then monitored for exceptions such as crashes, or failing built-in code assertions or for finding potential memory leaks. Typically, fuzzers are used to test programs that take structured inputs." [`https://en.wikipedia.org/wiki/Fuzzing`].
Impact to system assets - the insecure network can result in harm to the system's data confidentiality, integrity, and availability or denial of service. Can also be a reason for launching attacks on other systems' devices.
Impact to business assets - denial of service attack could lead to users' data loss of availability along with data loss.
Possible attack examples:

(i) Fuzzing attacks. Let us consider an example of fuzzing attack with a Burp Suite Intruder and an OWASP WebGoat application. An attacker here with means to log into the app as Admin user without the password.

(ii) Some ports are open and are not monitored by the system, so could be accessed via UPnP.

4. **Lack of Transport Encryption, V#4:**
Threat agent - an attacker with an access to the network the IoT device is connected to.
Attack method - attacker uses the lack of transport encryption to view data being passed over the network.
Vulnerability - lack of transport encryption is a common vulnerability for local networks as it is assumed that in the local and wireless networks the traffic will not be widely visible and accessible. However, it makes all the data transferred through such networks visible for a possible attacker in range of the wireless network support or with external access to the local network.
How to discover - many issues with transport encryption are easy to discover simply by launching a testing attack on the system by viewing network traffic and searching for readable data in it. Automated tools can also look for proper implementation of common transport encryption such as SSL and TLS.
Impact to system assets - insecure web interface could result in harm to service's data confidentiality, integrity, and availability which can then lead to complete device takeover.
Impact to business assets - the actual device or whole IoT System could be compromised along with the users.
Possible attack examples:

(i) The cloud interface uses the only HTTP.

(ii) User-name and password are transmitted in the clear over the network.

5. **Privacy Concerns (Confidentiality), V#5:**
Threat agent - an attacker with an access to the IoT device itself, the network the device is connected to, the mobile application and the cloud connection.
Attack method - an attacker uses insufficient authentication, lack of transport encryption or insecure network services to break systems' data confidentiality.
Vulnerability - all vulnerabilities of authentication/authorization, low protected transport protocols and not appropriate secure network services.
How to discover - privacy concerns are easy to discover by simply reviewing the data that is being collected as the user sets up and activates the device. Automated tools can also look for specific patterns of data that may indicate a collection of personal data or other sensitive data.
Impact to system assets - harm to service's data confidentiality, integrity, and availability which can then lead to complete device takeover.
Impact to business assets - the actual device or whole IoT System could be compromised along with the users.
Possible attack examples:

   (i) Collection of personal data.

   (ii) Collection of financial and/or health information.

6. **Insecure Cloud Interface, V#6:**
Threat agent - an attacker with an access to the internet.
Attack method - an attacker uses insufficient authentication, lack of transport encryption and account enumeration to access data or controls via the cloud interface (website).
Vulnerability - low-level security of the cloud access credentials or account enumeration is possible.
How to discover - insecure cloud interfaces are easy to discover by simply reviewing the connection to the cloud interface and identifying if SSL is in use or by using the password reset mechanism to identify valid accounts which can lead to account enumeration.
Impact to system assets - harm to service's data confidentiality, integrity, and availability which can then lead to complete device takeover.
Impact to business assets - the actual device or whole IoT System could be compromised along with the users.
Possible attack examples:

   (i) Password reset indicates whether the account is valid.

   (ii) User-name and password are poorly protected when transmitted over the network. In such cases, an attacker is able to either determine a valid user account or capture the credentials as they cross the network and decode them since the credentials are only protected using Base64 Encoding.

7. **Insecure Mobile Interface, V#7:**
   Threat agent - an attacker with access to the mobile application.
   Attack method - an attacker uses insufficient authentication, lack of transport encryption and account enumeration to access data or controls via the mobile interface (application).
   Vulnerability - low-level security of the app access credentials or account enumeration is possible.
   How to discover - insecure mobile interfaces are easy to discover by simply reviewing connection to the wireless networks and identifying if SSL is in use or by using the password reset mechanism to identify valid accounts which can lead to account enumeration.
   Impact to system assets - harm to service's data confidentiality, integrity, and availability which can then lead to complete device takeover.
   Impact to business assets - the actual device or whole IoT System could be compromised along with the users.
   Possible attack examples:

   (i) Password reset indicates whether an account exists or not.

   (ii) User-name and password are poorly protected when transmitted over the network. In such cases, an attacker is able to either determine a valid user account or capture the credentials as they cross the network and decode them since the credentials are only protected using Base64 Encoding.

8. **Insufficient Security Configurability, V#8:**
   Threat agent - an attacker with an access to the IoT device.
   Attack method - an attacker uses the lack of granular permissions to access data or controls on the device, low-level transport encryption and the use of low-level passwords can also be the doors for the attack on the system.
   Vulnerability - insufficient security configurability is present when users of the device have limited or no ability to alter its security controls. If the web interface does not support creating granular user permissions and does not force user for creating a strong password.
   How to discover - detailed review of the web interface along with provided options can reveal existing vulnerability.
   Impact to system assets - harm to service's data confidentiality, integrity, and availability which can then lead to complete device takeover.
   Impact to business assets - the actual device or whole IoT System could be compromised along with the users.
   Possible attack examples:

(i) Strong passwords are not forced to be used, then an attacker is able to gain access to existing accounts using brood force methods.

(ii) Valuable data which is stored on the device is not encrypted, then an attacker is able to access data at rest which has just simple protection such as asking for administrator's credentials to view data.

9. **Insecure Software/Firmware, V#9:**
Threat agent - an attacker with an access to the IoT device and/or network the device connects to and/or the server which provides updates to the IoT devices Software.
Attack method - an attacker captures files with updates from an unencrypted connection between server and IoT devices. The files with updates are not encrypted itself. An attacker performs an unauthorized update of the system software via DNS hijacking.
Vulnerability - low system states monitoring, low level encryption. Devices should have the ability to be updated when vulnerabilities are discovered and software/-firmware updates can be insecure when the updated files themselves and the network connection they are delivered on are not protected. Software/Firmware can also be insecure if they contain hardcoded sensitive data such as credentials.
How to discover - security issues with software/firmware are relatively easy to discover by simply inspecting the network traffic during the update to check for encryption or using a hex editor to inspect the update file itself for interesting information.
Impact to system assets - harm to service's data confidentiality, integrity, and availability which can then lead to complete device takeover.
Impact to business assets - the actual device or whole IoT System could be compromised along with the users.
Possible attack examples:

(i) Update file is transmitted via HTTP then an attacker is able to change them on their way from server to device.

(ii) Update file is unencrypted and human-readable data can be viewed.

In the cases above, the attacker is able to either capture the update file or capture the file and view its contents.

10. **Poor Physical Security, V#10:**
Threat agent - an attacker who has physical access to any physical system asset.
Attack method - an attacker uses vectors such as USB ports, SD cards or other storage means to access the Operating System and potentially any data stored on the device.
Vulnerability - Physical security weaknesses are present when an attacker can

disassemble a device to easily access the storage medium and any data stored on that medium. Weaknesses are also present when USB ports or other external ports can be used to access the device using features intended for configuration or maintenance.
How to discover - detailed review of the hardware components of the IoT system.
Impact to system assets - harm to service's data confidentiality, integrity, and availability which can then lead to complete device takeover
Impact to business assets - the actual device or whole IoT System could be compromised along with the users.
Possible attack examples:

(i) The device can be easily disassembled and the storage medium is an unencrypted SD card.

(ii) USB ports are present on the device then an attacker is able to change device software or stole valuable data from it.

4.3 IoT Security Controls

During the SRM process in IoT determining possible risks is not the only step in securing system. It is always important to know how to cover existing vulnerabilities in order to mitigate possible risks. In the IoT, securing process requires a holistic understanding of security controls for all assets of the system. Security mechanism should be unique for each valuable element of the system as it has to follow elements' lifecycle and functionality provided to the system. In this section, we allocate and describe ground keys in securing IoT systems and propose appropriate countermeasures for covering different types of systems' vulnerabilities [32].

4.3.1 Protocol and Network Security

Protocol and network security often require optimizations in cryptography algorithms and appropriate key management systems, as cryptography plays a leading role in developing security protocols for securing network infrastructure. However, applying standard Internet security mechanisms to the functional assets of the IoT system could be inefficient due to the lack of the assets' resources. Therefore, security protocols should be adapted based on the assets' architecture taking into account their performance and capabilities. According to the Open Web Application Security Project [45] we can propose next security countermeasure to apply protocol and network security on an appropriate level:

1. **Secure Network Services, Cm#1:**

- Only necessary ports which are crucial for the appropriate system functionality should be exposed and available.
- Service should be protected from buffer overflow (overrun) [49] and fuzzing attacks [50].
- Ensure that the service is prepared and not vulnerable to DoS attacks [51] or at least monitoring system is provided to determine such type of an attack.
- Ensure that network ports and services exposed to the internet via UPnP for example.
- Monitoring system should also detect abnormal service request traffic and block gateways if necessary.

2. **Transport Encryption, Cm#2:**

   - Always use transport protocols such as SSL [52] and TLS [52] while data transferring through network to be sure that your data is encrypted.
   - If SSL or TLS are not available do not hesitate to use other standard encryption methods to protect data.
   - Pay attention what encryption techniques are used. Avoid using unaccepted encryption standards.
   - Use MQTT payload encryption [53] to protect system's specific data on the application level.
   - Ensure to use secure encryption key handshaking.
   - Always verify incoming data for integrity.

Countermeasure on secure network services (Cm#1) mitigate risks with vulnerabilities of insecure network services (V#3), and communication encryption (Cm#2) – vulnerabilities related the lack of communication encryption (V#4).

4.3.2 Data and Privacy

Data and privacy key often represented by the most sensitive and valuable assets of the IoT system. Each user wants their personal data to be protected and managed by themselves, but there are a lot of systems which based on managing users' data. In such cases, a huge issue is to constrain and monitor the list of accepted data managers. Consequently, using cryptographic algorithms and different protocols for secure data transferring could be not enough. In other words, it should be developed special management policy based on the data type managed by the system. We can propose next countermeasures [45]:

1. **Privacy Concerns, Cm#3:**

- While collecting data be sure that: (i) only critical to the functionality of the system data is collected; (ii) avoid collecting sensitive data; (iii) collected data is de-identified or anonymized; (iv) retention limits are set for the collected data; (v) protect collected data with encryption.
- Ensure that personal information is properly protected on all levels of the system.
- Give access to the collected data only for authorized users.
- Do not collected more data that actually needed for appropriate functionality of the system.
- Always de-identify data before analyzing.

2. **Secure Software/Firmware, Cm#4:**

    - Ensure that the system uses secure update mechanism and all files transferring is based on accepted encryption methods.
    - The update file should not expose sensitive data.
    - Each pack of incoming files with updates should be signed and verified before even saving in system memory storage.
    - Use only trusted and secure servers for updates.
    - If possible, its recommended to use secure boot ("Secure Boot is a technology where the system firmware checks that the system boot loader is signed with a cryptographic key authorized by a database contained in the firmware." [55]).

3. **Physical Security, Cm#5:**

    - Use only trusted and protected data storage services that can not be easily removed.
    - All sensitive system's data should be encrypted at rest.
    - Always check that USB ports or other external ports are protected from uploading malicious software through.
    - It is recommended to minimize the number of external ports such as USB used by the system.
    - "Ensuring the product has the ability to limit administrative capabilities" [45].

Countermeasures regarding the privacy concerns (Cm#3) help to mitigate security risks with vulnerabilities related to privacy concerns (V#5); secure software and/or firmware (Cm#4) – vulnerabilities related to insecure software and/or firmware (V#9). Countermeasure of physical security (Cm#5) address risks with vulnerabilities of poor physical security (V#10).

4.3.3 Identity Management

Identity management represents a non-trivial process of verifying a staggering variety of identity and connection types. We can allocate a key rules which should be followed during IoT system identity management:

1. An object's identity should always be unique compared to the other objects from its family.

2. Unique identity can be called core identity, as an object can also have several temporary identities.

3. Self-identification is one of the ground features of an object.

4. An object knows the identity of its owner if it exists.

One more important mechanism in identity management is to give an object opportunity to cover its identity if needed. As IoT systems cover different backgrounds of the humans' everyday life, there are situations when it is not safe to reveal identities only based on incoming requests. If look more precise at Identity management we can propose to follow next recommendations:

1. **Secure Authentication/Authorization, Cm#6:**

    - Ensure that strong usernames and passwords are always required.
    - Two factor authentication and users' credentials encryption should be implemented if possible.
    - Be aware of insecure password recovery mechanisms and be sure that "re-authentication is required for sensitive features" [45].
    - Revoking mechanism should be developed for the system's credentials.
    - Application, device and server authentication are always required.
    - "Manage authenicated user id(credential info.) and the user's device id, the user's app id mapping table in the authentication server" [45].
    - Authentication token/session should always be unique to each user along with user id, app id and device id.

2. **Secure Web Interface, Cm#7:**

- Default username and password should be non trivial and its recommended to change them during initial setup.
- "Forgot password" functionality should be secure and sturdy. Be sure that you do not provide user with information indicating valid account.
- Always check if your Web Interface is protected from XSS (Cross-site Scripting) [46], SQLi (SQL injections) [47] or CSRF (Cross-site request forgery) [48];
- Do not hesitate to use only encrypted transport protocols while transferring system's credentials.
- Do not allow usage of low level passwords.
- Set appropriate number of attempts that allowed while logging in to the system. If the number was exceeded it is recommended temporary block the user for further authentication procedures if needed.

3. **Secure Mobile Interface, Cm#8:**

   - Default usernames and passwords should always be changed during initial setup.
   - Ensure you system is protected from account enumeration through password reset mechanisms
   - Set a limit for unsuccessful login attempts, so if it was reached the user is temporary blocked.
   - Try not to transfer system's credentials over the internet.
   - Two factor factor authentication should be implemented.
   - Its recommended to use obfuscation technique [54] applied to mobile app of the system.
   - Restrict the mobile app's execution on tempered OS environment" [45].

Countermeasures to secure authentication and/or authorization (Cm#6) mitigate risks with vulnerabilities of insufficient authentication and/or validation (V#2); to secure Web interface (Cm#7) – vulnerabilities of insecure Web interface (V#1); and to secure mobile interface (Cm#8) – vulnerabilities of insecure mobile interface (V#7).

4.3.4 Trust and Governance, Cm#9:

Trust and governance the fundamentals of each IoT system. Represented by a mechanism which dynamically evaluates objects it helps to control users' services based on the interaction process. In pair with governance, trust plays the role of a framework in which key role is to support cohesion and stable work of the security protocols in the system. This key plays a crucial role for the systems which services rely on Cloud interface. According to [45] we can recommend next countermeasures:

- Default usernames and passwords should always be changed during initial setup.
- Ensure you system is protected from account enumeration through password reset mechanisms.
- Set a limit for unsuccessful login attempts, so if it was reached the user is temporary blocked.
- Cloud-based interface should be always protected from XSS (Cross-site Scripting) [46], SQLi (SQL injections) [47] or CSRF (Cross-site request forgery) [48];
- Try not to transfer system's credentials over the internet.
- Two factor factor authentication should be implemented.
- Monitoring system should detect abnormal service request traffic and block gateways if necessary.

Countermeasures regarding the trust and governance (Cm#9) deal with the security risks with vulnerabilities of insecure cloud interface (V#6).

4.3.5 Fault Tolerance, Cm#10:

Clearly, no IoT system can pretend to be entirely secure, since the number of possible threads rising significantly faster than the number of solutions for covering new-appeared vulnerabilities in the system. Accomplishing acceptable fault tolerance in IoT requires next interdependent efforts:

1. All objects have to be secure by default, it means that besides secure protocols and algorithms the comprehensive software structure should always be improved.
2. The state of the network and its services should be shared among all IoT objects. This will provide an opportunity to maintain states' monitoring management on an appropriate level as each object would be able to associate its own state changes with the network state changes. Consequently, the system monitoring quality will grow up.
3. Based on the second effort, each object should be able to protect themselves if the network state said about network collapse or attack. To arrange this functionality an intrusion-detection system should be introduced as well as other defensive structures.

4. Force system to separate normal users from administrative users.
5. Provide functionality to encrypt data, data at rest or in transit.
6. Force users to use only strong passwords during authorization/authentication processes.
7. "Ensuring the ability to enable logging of security events and to notify end users of security events".

Countermeasures regarding the fault tolerance (Cm#10) mitigate security risks with vulnerabilities of insufficient security configurability (V#8).

5 Analysis of Security Risks in IoT Systems

In this section we discuss few reported attacks examples on IoT. The purpose is to illustrate the IoT assets, risks, and their vulnerabilities; potentially the countermeasures discussed in Section 3 should be applied to mitigate these risks. Based on such strategy we introduce IoT Security Reference Model.

5.1 Examples of the IoT Security Risks

	Example 1 [58]	Example 2 [59]	Example 3 [60]
Threat agent	An attacker with means to break normal work flow of the popular web services.	An attacker with means to interrupt heating process of the buildings.	An attacker with means to slow down the work flow of the university servers.
Attack method	1) Infection IoT devices using Mirai botnet; 2) Overload servers using infected devices.	1) DDoS attack on the heating network.	1) Botnet which makes system do DNS lookups every 15 min; 2) Brute force method to hack weak passwords.
Vulnerability	1) Devices' Linux kernel version ran out of date; 2) Users did not change the default usernames/passwords on their devices.	1) Network was not under monitoring.	1) Weak passwords; 2) Low level network activity monitoring.
Impact	1) Major websites servers' overload; 2) Loss of routers and IP cameras confidentiality; 3) Loss of websites' services reliability.	1) Two buildings were left unheated in the freezing temperature; 2) Loss of heating controllers' reliability; 3) Loss of network confidentiality.	1) Harm to the system's network; 2) Harm to servers; 3) Negation of integrity of the system's data.

Table 2. Reported attacks examples

	Example 4 [61]	Example 5 [62]	Example 6 [63]
Threat agent	An attacker with means to publish the victim's data or perpetually block access to it unless a ransom is paid uses malicious software from cryptovirology.	An attacker with means to control another's car remotely.	An attacker with means to stole personal data or change stored data in the doll's DB.
Attack method	Malicious software from cryptovirology.	Uploading malicious software to the control module.	Bluetooth connection attack (Bluebugging).
Vulnerability	Was not mentioned but allegedly - low level monitoring of the system's incoming data (Ransomware attacks are typically carried out using a Trojan that is disguised as a legitimate file that the user is tricked into downloading or opening when it arrives as an email attachment).	Insecure transport protocol (UConnect (module installed on Chryslers) uses the GSM network to access Internet but it was unsecured).	An insecure Bluetooth connection.
Impact	1)Harm to 70% of the city's CCTV systems.	1) Harm to transport protocol of the UConnect system; 2) Negation of integrity of the car control commands; 3) Loss of vehicle control.	1) Loss of users' data confidentiality; 2) Negation of integrity of the data stored on the doll's database .

Table 3. Reported attacks examples

Based on the Table 2. and Table 3. above we can determine next security risks:

Risk 1: An attacker with means to break normal work flow of the popular web services uses Mirai botnet exploits that devices' Linux kernel version ran out of date and users did not change the default usernames/passwords on their devices which leads to major websites servers' overload, loss of routers and IP cameras confidentiality and loss of websites' services reliability.

Here the *business asset* is the cameras' IP supported by the Web services, Linux kernels, and other devices. The risk is possible because of the vulnerabilities V#2 (in Web service) and V#7 (in IoT device). It could be mitigated by a set of countermeasures selected from Cm#6 and Cm#8.

Risk 2: An attacker with means to interrupt heating process of the buildings uses DDoS attack on the heating network exploits that system's network was not under monitoring which leads to the fact that two buildings were left unheated in the freezing temperature, loss of heating controllers' reliability and loss of network confidentiality.

In this examples the *business asset* is the data sent over the network. This data is supported by (i.e., sent over) the heating network. The risk becomes possible because of the vulnerability V#3 in the network. This risk could be mitigated by countermeasures selected from Cm#1.

Risk 3: An attacker with means to slow down the work flow of the university servers uses Botnet and brute force password hack method and exploits low level network activity monitoring and weak passwords which leads to harm to the system's network, servers and data.

The *business asset* is the data used in the university workflow. This data is supported by the university and protected using passwords. The risk becomes possible because of the vulnerabilities V#3 in the network (i.e., the University servers) and V#2 in the provided service (i.e., activity/workflow supported by the server). This risk could be mitigated by a set of countermeasures selected from Cm#1 and Cm#6.

Risk 4: An attacker with means to publish the victim's data or perpetually block access to it unless a ransom is paid uses malicious software from cryptovirology and exploits (allegedly) the low level monitoring of the system's incoming data which leads to harm to 70% of the city's CCTV systems.

In this example the *business asset* is the victim's data supported by the network. The risk becomes possible because of the vulnerabilities V#3 in the remote storage and V#8 in the IoT system. This risk could be mitigated by a set of countermeasures selected from Cm#1 and Cm#10.

Risk 5: Two white hat-hackers with means to control another's car remotely used malicious software uploaded to the UConnect control module through insecure transport protocol (UConnect (module installed on Chryslers) uses the GSM network to access Internet but it was unsecured) and were able stop remotely Jeep Cherokee in the highway.

Here, the *business asset* is the car control commands supported by the UConnect module to sent them over the GSM communication channel. The risk becomes possible because of the vulnerability V#4 in the transport protocol (i.e., UConnect). This risk could be mitigated by countermeasures from Cm#2.

Risk 6: A white-hat attacker with means to stole personal data or change stored data in the "My friend Cayla" doll's DB, claimed to be the first world interactive doll, uses Bluetooth connection attack to exploit an insecure Bluetooth connection and modified doll's database. As a result, "My friend Cayla" was banned by German government, qualified as an "espionage device".

The *business asset* is a date supported by (sent through) the Bluetooth connection and (stored in) the doll's database. The risk becomes possible because of the vulnerabilities V#3 in the data storage (i.e., doll's database) and V#4 in the communication (i.e., Bluetooth communication). This risk could be mitigated by a set of countermeasures selected from Cm#1 and Cm#2.

Vulnerability itself represents only characteristic of an asset or a group of assets and describes weakness of the system. However, if we apply threats to different vulnerabilities a risk of a negative impact on system assets occurs. As a result, we can conclude that the combination of threats and vulnerabilities represents a main reason for both the risk event and its harmful consequences for the system [1].

5.2 IoT Security Reference Model

In this subsection we will show how we can combine IoT Domain Model from Figure 6 with the existing practice of covering vulnerabilities, provided by OWASP and reviewed in section 4.3, into IoT Security Reference Model (Figure 7). Such a model then could be used for a certain type of control design in IoT systems, since it will represent the desired behavior of IoT system components.

All functional elements of the presented Reference Model were described in previous sections. In our case vulnerabilities from section 4.2, according to Risk Management pattern, play a role of characteristics of the IoT system assets. Consequently, we can target countermeasures' techniques exactly to the asset which need to be protected. Starting from IoT system itself we can characterize its weakness as a V#8: *Insufficient security configuration*, which reveals the fact that the system has limited configuration functionality or no ability to alter its security controls. As a result, we should apply the Cm#10: *Fault Tolerance* and always be ready to tackle upcoming security issues. Although, *Vulnerability Reporting* functionality could be a useful solution in such case when providing the additional secureness of the system is much more expensive than expected revenue from the service itself. As each IoT System, according to our Domain Model, consist of *Service, Computing Device* and *Data Storage* we should not neglect the characteristical vulnerabilities of each of its elements. That is why we pointed Cm#7, Cm#4 and Cm#5 to the IoT system sub-elements. Further, it will help us to determine, which actual technique we should use and where to apply it in order to provide secure service to the user, protect computing power of the system and do not allow unauthorized access to the stored data. IoT Devices such as sensors, machines and intelligent edge nodes represented by system asset *IoT Device* bring in to system V#5 and V#10 which should be covered by Cm#3. *Network Resources & Remote Storage* suffer from *Insecure network services* and possible connected risks can be mitigated with Cm#1. One more system asset which interconnects IoT Devices in the system is represented by *Connection* and the vulnerability of *Lack of communication encryption* supposed to be covered with Cm#2. Finally, *Cloud* asset can be characterized by *Insecure cloud interface & Poor physical security* and consequently the application of Cm#9 is needed.

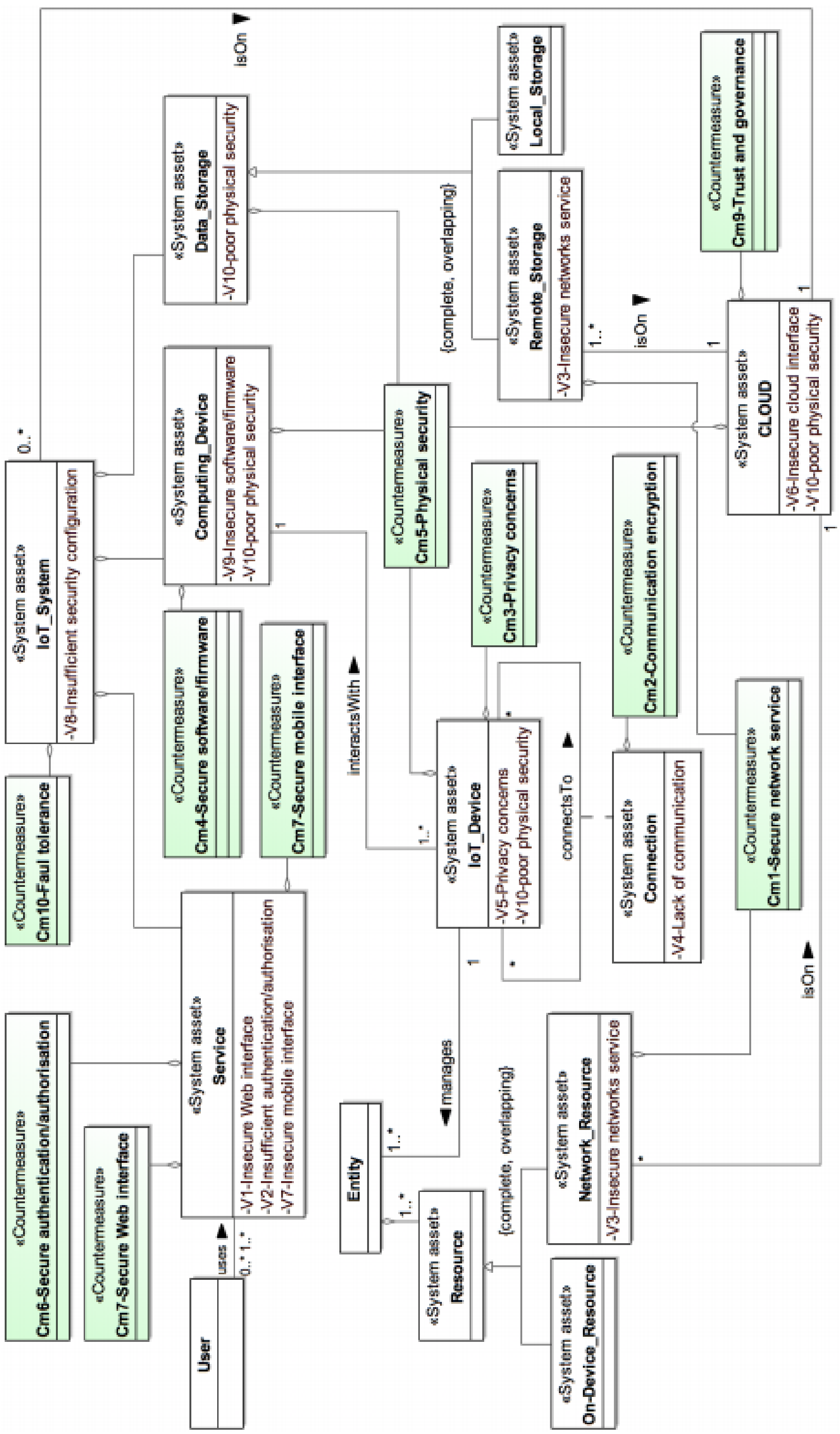


Figure 7. IoT Security Reference Model.

6 Framework Application for the IoT system

To illustrate the SRM process we decided to take as an example arguably one of the most known IoT system - Smart Home [31]. Since Smart Home is considered as an essential domain in IoT, we can use its wide architecture to show how such automated IoT system raises a great concern of the privacy and security due to the heterogeneity of the interconnected elements and capability to be controlled remotely.

The basic idea about the project is to build a simple smart home prototype using different types of sensor modules controlled by Raspberry Pi, which will then store aggregated data in the cloud. Consequently, the user will be able to get data from the cloud, monitor real-time system state and send commands to the control center. Then show how such a system could be effected through uncovered vulnerabilities of its elements. And finally, apply the previously developed framework in order to mitigate possible risks.

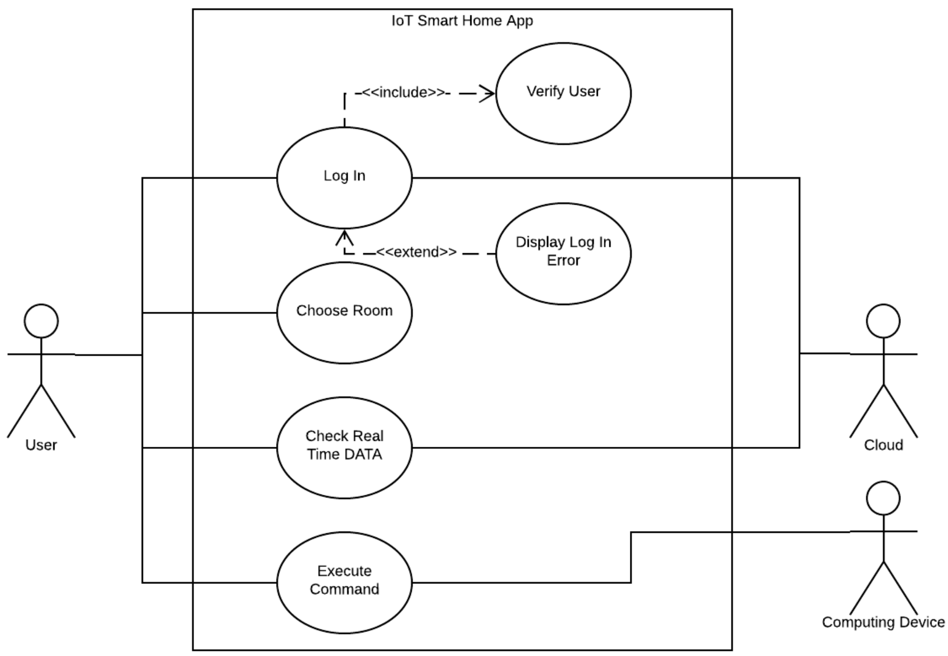


Figure 8. Smart Home App Use Case Diagram.

6.1 IoT System Architecture

Lets start with the Figure 8, which represents Smart Home App Use Case Diagram. We can determine three main actors: 1) *User*; 2) *Cloud*; 3) *Computing Device*. *User* can Log In into the App, Choose Room to check DATA from and based on the data Execute Commands. *Cloud* as an actor takes part in Log In and Checking Real Time DATA processes, while *Computing Device* executes commands received from the *User*.

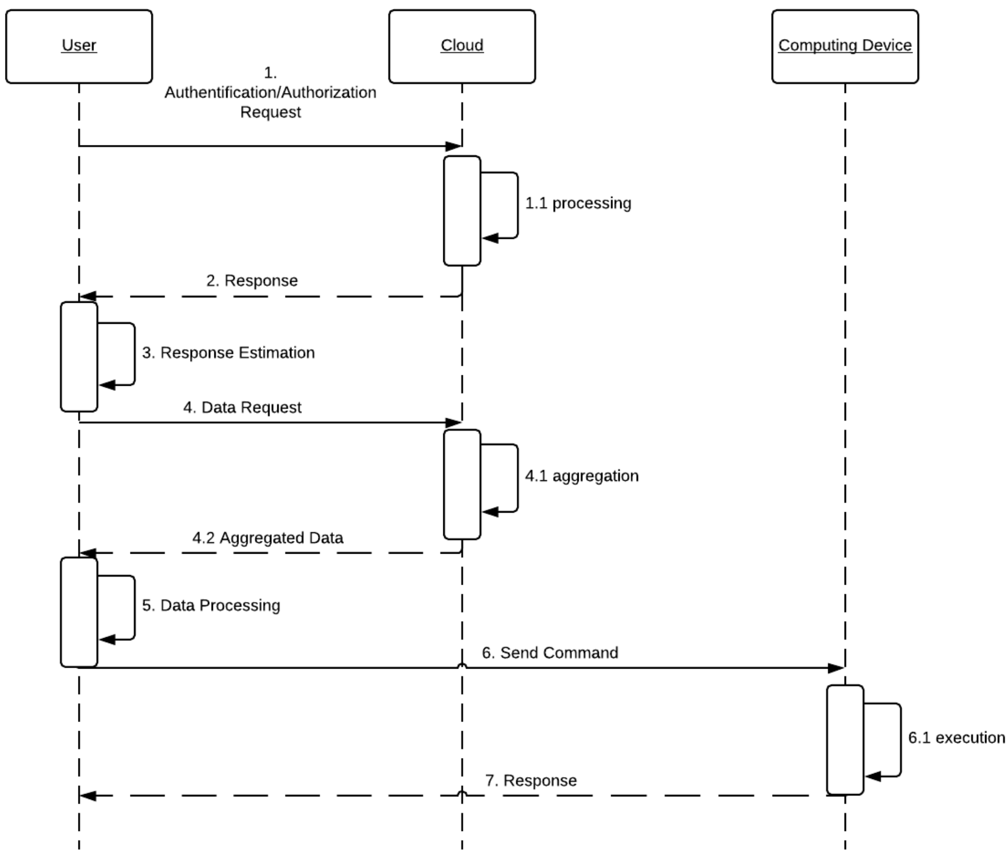


Figure 9. sHome App Sequence Diagram.

If we look at Figure 9, we can see how the actors from the Figure 8 communicate with each other. *User* sends authentication/authorization request with credentials to the *Cloud*, which processes incoming request and, if credentials are matched, gives positive response to the *User*, otherwise negative. Consequently, based on the *Cloud's* response *User* will be given an access to the Smart Home application functionality or asked to check Log In credentials. If the Log In processes finishes successful *User* can request

Real Time DATA from the *Cloud*, which will be displayed in the App. After evaluating DATA *User* can send a command to the *Computing Device*, which will then try to execute the received command and provide *User* with an appropriate response message.

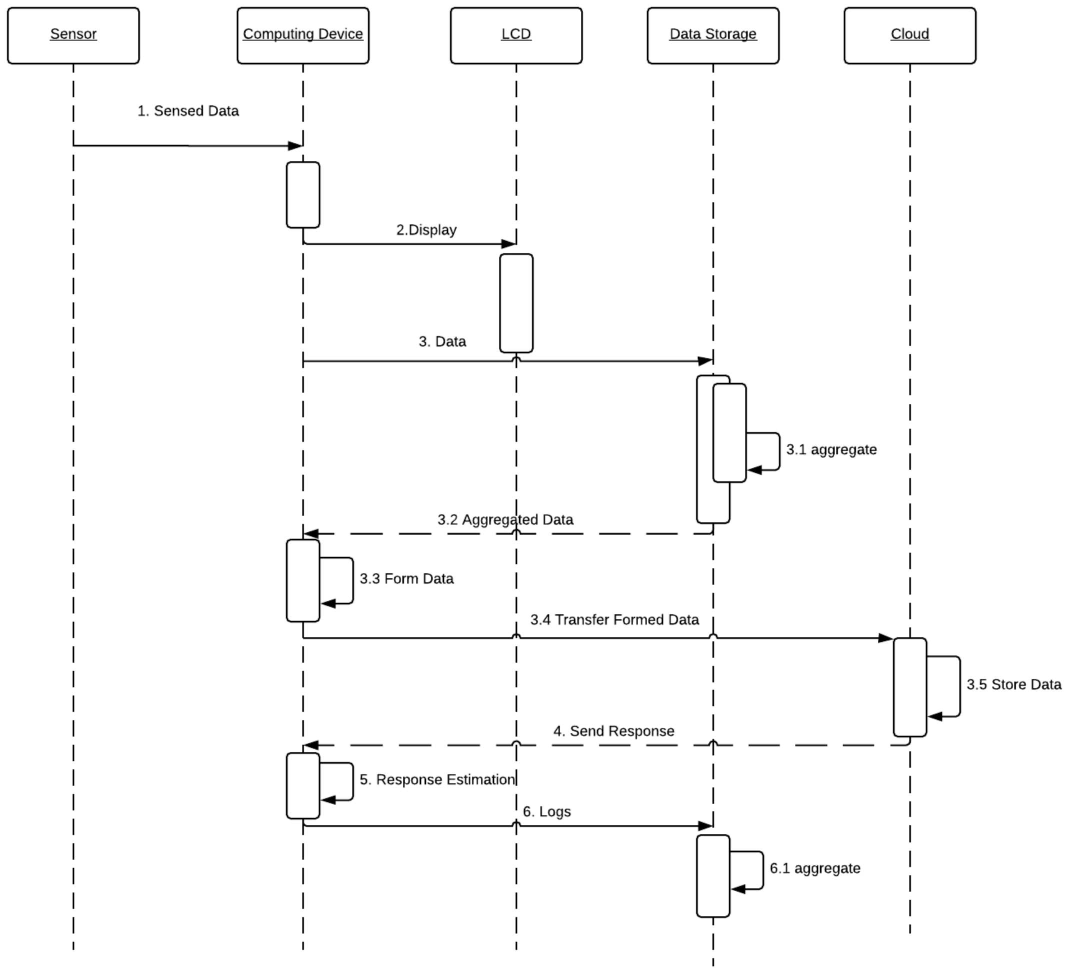


Figure 10. sHome IoT system Sequence Diagram.

Now lets dive dipper into the actual Smart Home IoT system architecture. From the Figure 10, we can see that the actual workflow of the system starts by collecting Sensed Data from each available *Sensor* in the system. Then this Data is displayed on *LCD* screen, so you can monitor system state at home without using application. Sensed Data then is stored in local Data Storage and, when data from each sensor is aggregated, it is formed on *Computing Device* and transferred to the *Cloud*. On *Cloud* data is stored in database and *Computing Device* receives response from *Cloud* if the data was stored successfully or not. Based on received response *Computing Device* create Logs and store them in the local *Data Storage* as a .log file.

6.2 Application Security

Now we can show how the IoT Security Reference Model (Figure 7) can be used during the application development process. If we look at sHome App Sequence Diagram (Figure 9) we will see that during first step we should provide secure Authentication/Authorization, according to Cm#6 (see sec. 4.3.3) we will use two-factor authentication based on the user's mobile phone number. To enter the app view from which you can start operating with the smart home environment you have to:

1. If the user is on authorization stage, he or she is asked to provide his mobile phone and set a password. Password itself is checked for trivialism, and passwords with the length less than eight characters and which consist only of letters of digits will not be accepted. After the password is set, the system tries to verify user's mobile phone by sending verification code and asking a user to enter it in an appropriate field. As soon as the mobile phone is verified the user is given an access to the app functionality.

2. In case of authentication stage, the user is asked to enter a password from the authorization stage and if it matches the verification code will be sent to the user's mobile phone. The next step is the same as during the authorization process.

Instead of storing user's personal data on a device, which is unsafe and can lead to its leakage, we transfer previously entered e-mail and mobile phone to the Cloud, where they are stored in an encrypted way (while such data is in rest, it should be encrypted). To secure private data, which is transferred from device to the Cloud we follow Cm#2 and use encrypted transport protocol HTTPS for the Cloud along with Axios JavaScript library which has built-in CSRF protection and supports upload progress, which could be crucial while uploading big files. To encrypt data in rest on Cloud we use *bcrypt*, which is a password hashing function designed by Niels Provos and David Mazières. We encrypt both password and mobile phone number before storing it in the database. Such a strategy will protect users data even if the entire database will be stolen. Unfortunately, even encrypted passwords can be cracked with different tools such as 'John the Rippe' `http://www.openwall.com/john/`, that is why we should always force user to create non-trivial passwords during authorization process. However, we should not only provide secure communication between user and Cloud but also should take care of how Computing device, which collects data from sensors, transfers it to Cloud and how the user can send commands to the control center of the IoT sHome system. To provide secure communication between a user and IoT computing device we use MQTT (Message Queue Telemetry Transport), which is an ISO standard (ISO/IEC PRF

20922) publish-subscribe based "lightweight" messaging protocol, while communication between computing devices and Cloud is built on top of HTTPS protocol. According to Cm#3, we build our Cloud based on widely-used, tested, secure, signature-based protocol OAuth1 [18]

6.3 Testing Results

Before applying countermeasures selected in sec. 6.2 lets see what can happen to our IoT sHome system if we leave its vulnerabilities uncovered.


```
{ "_id" : ObjectId("5b68a315cf750370cc1cf065"), "password" : "test1", "mobile_phone" : "123456783", "__v" : 0 }
{ "_id" : ObjectId("5b68bc44d96d4373ea5627e2"), "password" : "test", "mobile_phone" : "736364233", "__v" : 0 }
{ "_id" : ObjectId("5b68bc4fd96d4373ea5627e3"), "password" : "testtest", "mobile_phone" : "98509285049", "__v" : 0 }
{ "_id" : ObjectId("5b68bc5bd96d4373ea5627e4"), "password" : "qwerty", "mobile_phone" : "45235236", "__v" : 0 }
{ "_id" : ObjectId("5b68bc66d96d4373ea5627e5"), "password" : "565655", "mobile_phone" : "783478", "__v" : 0 }
```

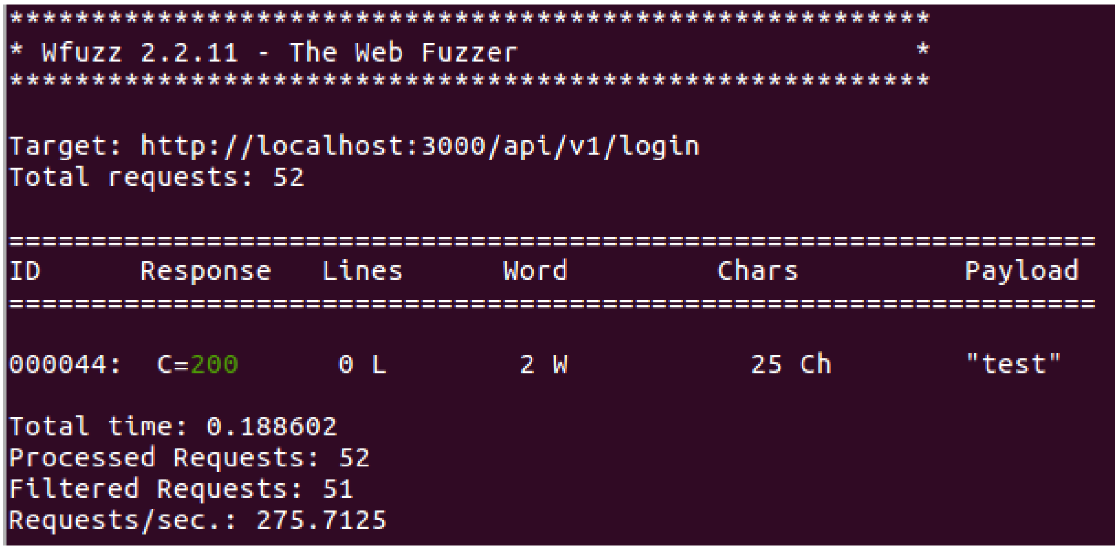

Figure 11. Unencrypted credentials in rest.

Let us start with viewing differences between encrypted and unencrypted data in rest. As we can see from the Figure 11 unencrypted passwords and mobile phones are visible as a human-readable data. Consequently, if the entire sHome system database will be stolen or remotely viewed all users' credentials will be revealed to the attackers. After applying the encryption algorithm on the data being in rest we can see that all credentials are no more in human-readable format (see Figure 12). In such case, we will have at least additional time to recognize the data leakage while an attacker is trying to decrypt stolen data. So the service will be able to force users to change their credentials. As a result, till the time when stolen data is decrypted, it will no more actual.


```
> db.smartusers.find()
{ "_id" : ObjectId("5b689580f566765323dc9ea8"), "password" : "$2b$10$nj32pPctKZHa/3bFTb1TzenEzur5gDpOXqth9Q1zrKX2dLS3oowSm",
"mobile_phone" : "$2b$10$nj32pPctKZHa/3bFTb1Tze0k.L2rW89xipcJGLJmjCq3LwUUn28OC", "__v" : 0 }
{ "_id" : ObjectId("5b68973f54b6c054c96ce1ae"), "password" : "$2b$10$Uxdd.26x7yjCIiBcReVKv.A6pbjfhKO2AQHuHQC5YcRP3o5jp.4GO",
"mobile_phone" : "$2b$10$Uxdd.26x7yjCIiBcReVKv.F4ZzWazfeOxbcHRoL74M1EsP.7qpz8e", "__v" : 0 }
{ "_id" : ObjectId("5b68974d54b6c054c96ce1af"), "password" : "$2b$10$FfST3ivPyFF2tr5LFm6L5.hmcX7nSjxR8V7oAxNgx1kTBbrZExOt6",
"mobile_phone" : "$2b$10$FfST3ivPyFF2tr5LFm6L5.Cdnbts.oaC0k3qQMZYPnwbDZQnt1eXq", "__v" : 0 }
{ "_id" : ObjectId("5b689765f1037b5527bcd319"), "password" : "$2b$10$vkEPOnx9uGZChA/DYWGw..TCHU3H1KRcNzfLeKcJMnJshfPs/0.rm",
"mobile_phone" : "123456783", "__v" : 0 }
{ "_id" : ObjectId("5b689f54f1037b5527bcd31a"), "password" : "$2b$10$FmmDKtrwCbMrqs5LHJZ7f.fAYgNYPErFBPC83wpGNeUkYrXQ7x3Ki",
"mobile_phone" : "123456783", "__v" : 0 }
```


Figure 12. Encrypted credentials in rest.

Next case is a gaining of an unauthorized access to the system through launching brute force attack on authentication gateway of the system, which is responsible for giving access to the Cloud for the computing device, which collects data from sensors. We will use WFuzz, which is a web application security fuzzer tool and library for Python. According to open source documentation, Wfuzz can set an authentication header by using the –basic/ntlm/digest command line switches. In our case, a protected resource using Basic authentication is fuzzed:



```
********************************************************
* Wfuzz 2.2.11 - The Web Fuzzer                        *
********************************************************

Target: http://localhost:3000/api/v1/login
Total requests: 52

==================================================================
ID       Response   Lines      Word         Chars          Payload
==================================================================

000044:   C=200       0 L        2 W          25 Ch         "test"

Total time: 0.188602
Processed Requests: 52
Filtered Requests: 51
Requests/sec.: 275.7125
```

Figure 13. Brute force attack.

As we can see from the Figure 13 it was needed 52 requests and 0.188 seconds to find out appropriate low-level password "test". Even in case of using more complicated and long password we can not guarantee secureness of the system authentication process, as it will take some finite amount of time to brute force a correct one credentials. After applying signature-based protocol OAuth1, we protect our Cloud API from such fuzzing attacks, as endpoints are no more constant and appropriate key is needed to make service respond on provided requests. The same scenario can be faced with brute forcing user credentials for the sHome App authentication, however two-factor authentication approach will cover this vulnerability, as an attacker will also need an access to the user's smartphone itself. Consequently, we come up with the case where V#10 (vulnerability of *Poor Physical Security*) is present, that is why the user himself should be attentive to his carry-on IoT devices.

According to sec. 4.3.3 we identify each sensor in the system with unique id which is then stored in computing device. So in case an attacker replaces system's sensor with malicious one, the computing device will not identify it as an authorized "thing" and reject collecting data from it, consequently, appropriate log information will be saved and provided to the user or a person responsible for system monitoring process management. Before integrating sensors' authorization, we were able to replace a temperature/humidity sensor DHT22 with the malicious one (the same one model DHT22, but which always returns the same temperature) and system went on working and collecting wrong data.

7 Conclusion

In this paper, we have aligned the IoT system components to the ISSRM asset [21] [1]. Then, following the OWASP [45], the vulnerabilities and countermeasures to mitigate them were highlighted. This potentially results in a reference model for securing IoT systems. We apply this initial reference model to the reported IoT security risks to illustrate instantiations of the IoT security risk concept. Finally, we have shown how the developed model could be used while developing real word IoT system in order to provide secure service to the users.

7.1 Limitations

The current reference model contains few limitations. Firstly, it basically covers the system assets and their vulnerabilities but leaves the analysis of business assets (i.e., data exchanged in the IoT systems, business operations) and their security criteria aside. Regarding the security risk analysis, we have concentrated on the vulnerabilities, but further work is needed to highlight the profile of the threat agents, their attack methods, as well as the impacts on the IoT system and business assets. On the system countermeasure side, we make an assumption that to treat IoT security risk one takes risk reduction decision; however it is also important to understand the consequence of other treatment decision (e.g., risk avoidance, retention or transfer). Finally, in our proposal, we do not differentiate between the security requirements and controls.

7.2 Inference

As we can see from Section 6.3 IoT Security Reference Model helps us precisely target countermeasure techniques to the IoT system's layers during development process in order to cover existing vulnerabilities. Such approach of aligning IoT system components to the ISSRM assets gives us opportunity to build a secure and protected architecture for the IoT system from scratch. As it was shown, in case of neglecting possible security risks we put valuable data under threat and make provided service unreliable and insecure. Consequently, such fragile systems can bring new risks in stack connected to beneficial services provided by the IoT.

7.3 Future work

In the future research, we plan to strengthen the proposed reference model with the definition of the explicit guidelines for the IoT asset, risk, and risk countermeasure identification, as well as the method of the security trade-off analysis. We have also planned to put our hands-on case (IoT sHome App) on more precise penetration testing, for which additional literature and tools study will be needed, as we will try to stole data from protected with developed framework system. Hopefully, during such tests the relationship among the IoT assets, their vulnerabilities, and proposed countermeasures will be explored in a more detailed way and give us more points to further framework development.

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