Bachelor Degree Project

UNIVERSITY OF SKÖVDE

THE FRAGMENTED SMART HOME:

A comprehensive analysis of available interoperable solutions to connect wireless smart home communications

DET SPLITTRADE SMART HEMMET:

En omfattande analys av tillgängliga interoperabla lösningar för att ansluta trådlös smarthems kommunikation

Bachelor Degree Project in Information Technology with a focus on network- and system administration
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Abstract

The current smart home communication can be viewed as protocol stacks interlocked by their proprietary capsule solutions, locking the consumer into a single market of devices, without integration from other manufacturers. This research heads out to discover frameworks to adapt the heterogenous proprietary communicative offerings within the smart home, to a shared communicative interoperable and centralized controlled home, to enable the end-user to adapt the most efficient device for each scenario without having to consider which wireless communicative protocol or having to install more proprietary solutions to adapt additional technologies, thus neglecting centralized control. The research is accomplished by conducting a structured literature review followed by an analysis through thematic coding which provided a broad spectrum of findings regarding different interoperable solutions within several layers of communicative interoperability, within IoT and the smart home. The research results cover frameworks and protocols towards accomplishing wireless interoperability discovered during the structured literature review process, these frameworks and protocols are presented in their respective characteristics, taking communication, interoperability, and smart home adaptation into consideration during analysis. The finalized results present solutions toward an interoperable wireless smart home with good adaptability, along with the main findings a clear redlining can be drawn towards interoperability within IoT, and it is Software Defined Networking (SDN), which revolves around software-based networking. The most applicable interoperable solutions according to the concluding results will provide experienced end-users, consumers, and researchers with a several layered mapping towards how applicable the corresponding solution is towards integrating wireless smart home communication in their smart home scenario.

Sammanfattning

Den nuvarande smarthemskommunikationen kan ses som stackar av protokoll sammankopplade av deras egen proprietär kapsellösning, vilket låser konsumenten till en enda marknad av lösningar, utan integration från andra tillverkare. Denna forskning ger sig ut för att upptäcka ramar för att anpassa de heterogena proprietär kommunikativa erbjudandena inom det smarta hemmet, till ett delat kommunikativt interoperabelt och centraliserat hem, så att användaren kan anpassa den mest effektiva enheten för varje scenario utan att behöva överväga vilket trådlöst kommunikationsprotokoll som fungerar eller att behöva installera mer heterogena lösningar för att anpassa ytterligare tekniker och därmed utesluta centraliserad kontroll. Forskningen genomfördes genom att utföra en strukturerad litteraturstudie följt av en analys genom tematisk kodning, vilket gav ett brett spektrum av resultat angående olika interoperabla lösningar inom flera kommunikativa lager av interoperabilitet presenteras i denna studie, inom både IoT och det smarta hemmet. Resultatet som presenteras täcker lösningar och protokoll inom kommunikation för att åstadkomma trådlös interoperabilitet i flera lager när det gäller både det kommunikativa och interoperabilitetsfunktioner, de presenteras i sina respektive egenskaper och tar hänsyn till både kommunikation och interoperabilitet när de kategoriseras i motsvarande tabeller, det avslutande resultaten inom analysen presenterar lösningar mot ett interoperabelt smarthem med hög anpassningsförmåga för just smarthemsmiljö. Utöver huvudresultatet, kan en tydlig rödtråd mot interoperabilitet i det smarta hemmet och IoT dras, och det är Software Defined Networking (SDN), vilket involverar mjukvarubaserad nätverkskommunikation. De mest tillämpliga lösningarna inom interoperabel kommunikation som sammanfattas i slutskedet ger erfarna användare, konsumenter och forskare en kartläggning i flertal lager mot hur tillämplig motsvarande lösning är mot ett interagerat trådlös baserat smarthem i respektive scenario.

Acknowledgements

A big acknowledgement to my supervisor Dennis Modig which through the process of this study gave me guidance towards continuously improving my work. The same goes for my examiner Ali Padyab, which from the get-go guided me in the process of undertaking such a big task as one's bachelor's degree project. I am deeply grateful for the continues support from both my supervisor and examiner and without them the integrity of this paper would not be the same, thank you so much!

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1 Introduction

Smart home devices form a network of nodes within the home to automate day-to-day tasks for the consumer, to adapt the home into an efficient, comfortable, and safe environment. (Farooq, Wheelock and Pesch, 2020, p. 22). The smart home technology has been on a steady uprise the past years and so has the heterogeneity between the available technologies, with a highly diversified nature as they assess different appliances within the smart home environment. Devices in the smart home can range from a lot of appliances, entertainment, security, environmental, monitoring and data logging are some examples (Mohamed, Perumal, Sulaiman, Mustapha and Yamaguchi, 2018).

With the increasing rate of smart home solutions and utilization of them in the consumer sector, it makes it possible to question interoperability between these offered solutions and devices. As the offered solutions and devices relate to a broad spectrum of communicative solutions used to apply functionality to these devices. Spanning from communicative network protocols such as Bluetooth, Wi-Fi, KNX-RF, EnOcean, Z-WAVE and ZigBee (Farooq, Wheelock and Pesch, 2020).

Some of these network protocols excel in bandwidth, others in the communicative range capabilities and some in the ability to remain close to energy neutral while operating.

Discussions of network protocol superiority can and has been made, as the interoperability issue would become exceedingly easy to solve if there was no network protocol competition on the market (Courreges, Oudji, Meghdadi, Brauers and Kays, 2016).

As described by (Farooq, Wheelock and Pesch, 2020, p. 22), "However, the current market opportunity is leading to many devices from different manufacturers lacking interoperability due to the multitude of communication standards and proprietary protocols in use.".

With the range of heterogeneous devices that exist in the smart home environment, a major hurdle is set for the adoption and deployment of this technology (Tooba, Muhammad and Martinez-Enriquez, 2018).

As smart home devices have a broad span of use cases, one communicative solution may also not be the most effective across all devices in terms of power efficiency and bandwidth efficiency. For example, a temperature sensor may utilize a ZigBee mesh-network to communicate and an infotainment system the home Wi-Fi (Farooq, Wheelock and Pesch, 2020).

As there is academically presented frameworks towards smart homes for the end-user, so post-facto interoperability is possible to apply even though the communicative protocols may differ from each other (Farooq, Wheelock and Pesch, 2020; Banerjee et al. 2018; Perumal, Ramli and Leong, 2011; Mao, Li, Zhang and Liang, 2017). This would allow the end-user a centralized platform to access and maintain all devices, no matter the communication protocol used by the smart device. Some of the available and presented frameworks come with application-level solutions to heterogeneity too, as the data syntax between manufacturers are not uniform neither. Proposed ideas of frameworks utilizing the cloud as the centralized controller are also discussed (Farooq, Wheelock and Pesch, 2020).

One thing to consider is that the typical end-user in smart home scenarios does not always possess the knowledge or technological skill on how to adapt and overcome the heterogeneity of these devices, as the devices do not always natively interoperate (Mainetti, Mighali and Patrono, 2015).

To apply adaptability within the smart homes, an assessment of different solutions is sought and as such this current study aims to summarize and compile current efforts towards interoperability, to provide a reasonable understanding on how interoperability can be adapted in heterogenous environments within the smart home. Accomplished by assessing available solutions through a systematic literature review, by assessing available published journal and papers hosted on online databases, the material then analysed by a thematic coding approach which revolves around categorizing these results.

This study does however neglect detailed explained adaptation, but instead categorize available protocols, frameworks, and solutions towards interoperability and as such some of the discussed solutions will require reasonable knowledge within the area to reach adaptation, moreover some solutions presented are at the opposite spectrum of accessibility and as such is accessible to a broader range of users.

2 Background

The idea of achieving complete interoperability in the smart home environment is not new, different approaches have been presented to transform the smart home communication and proprietary protocols which it uses, to a more open standard, to be able to integrate any heterogeneous data (Perumal, Ramli and Leong, 2011).

Interoperability problems within IoT and smart homes come both in the communicative technology levels such as the proprietary protocols, Z-Wave for example, and in the data syntax and semantic segment.

Semantic being revolved around the understanding of data while syntax is the format of data, according to the study by Tooba, Muhammad and Martinez-Enriquez (2018) the syntax interoperability issue is completely ignored while frameworks to solve the communication heterogeneous between different protocols is the focus in present-day work within the field, which neglect other interoperability areas according to Tooba, Muhammad and Martinez-Enriquez (2018).

Without data syntax-interoperability the issue persists, as such Tooba, Muhammad and Martinez-Enriquez (2018) present the idea of a middleware solution to eradicate heterogeneity in both affected areas to apply complete interoperability on all levels of communication.

Mainetti, Mighali and Patrono (2015) presents a similar IoT based user-centric ecosystem which addresses heterogeneity through multi-protocol middleware, as it was one of the requirements on the basis on how the user-centric ecosystem functions, providing dynamical automation depending on the users doing and position, location-aware services. As such the heterogeneous devices need to communicate despite the conflicting protocols they use. Their approach evolves around gathering a deep understanding of the different IoT standards, to define a common model that characterizes both device interactions and the physical aspect. By doing so, the multi-protocol middleware can map high-level requests on lower-level messages through the network, with this middleware layer the heterogeneity is abstracted from the underlying lower layers and makes it possible for the end-user to transparently communicate with any previously heterogeneous devices. This ecosystem works at a local level and the high-level layer is controlled by user mobile applications based on the RESTful interface (Richardson and Ruby, 2007; Mainetti, Mighali and Patrono, 2015).

Moreover, heterogeneous devices responsible for automation in the home are applied and defined by policies and rulesets which when the devices within the home are heterogeneous may conflict with each other's automation. Such when an event happens, the device will react with its property ruleset and trigger which could conflict with the trigger of another heterogenous device. To address these conflicts Mohamed et al. (2018) proposed a framework to detect any unpredictable behaviours to solve conflict related issues with real time conflict resolutions, this increased the run-time response with an average of 500% or 106,08 Ms slower average, compared to without the framework model. This was the average across all devices in the test but resolves any conflicting actions from the heterogeneous devices and improves system satisfaction (Mohamed et al. 2018).

Huang and Tseng (2016) present a way to tackle heterogeneous devices within the home by interoperating them and connecting them to the cloud, instead of trying to solve interoperability on a local level, they present a solution utilizing a terminal built by ARM Cortex-A7 and a Raspberry PI 2 single board computer which together with a wide-angle IR transmitter, IR receiver, Zigbee communication system, IP Camera and Internet is able to function as a terminal gateway with the heterogeneous devices within the home and forward communication to a cloud service set by this system, the cloud server environment used is called Amazon EC2. This allows for remote control, live monitoring, live view, and sensor value curves (Huang and Tseng, 2016).

2.1 Interoperability & IoT

This sub-chapter define interoperability within the IoT spectrum of devices as well as different layers and levels of interoperability regarding the communication protocol stack.

As worded by Samuel (2016), interoperability is defined as the ability of systems, applications, and services to work together reliably in predictable fashion.

Aly, Khomh, Guéhéneuc, Washizaki and Yacout (2019) set out to see how fragmented the IoT technologies are, to raise awareness to the community about the lack of interoperability within these technologies. The article covers a lot more than just the smart home spectrum of things but still provides a lot of relevance as to how smart homes are adapted as IoT commonly uses the same type of energy efficient communicative technologies. They also present a set of common solutions to tackle their findings, which provide useful insight on how interoperability may be achieved. They define IoT interoperability into three different categories from their findings, network-layer interoperability, messaging-protocol interoperability, and data annotation-level interoperability.

The technical- & networking layer contains the various networking standards and protocols such as ZigBee and Wi-Fi as examples, IoT wireless communication requires power constrained networking with easy deployment and as such it is of importance to function optimally for the device's application. This may also be referred to as technical interoperability.

Whereas messaging-protocol interoperability is based upon application level protocols, proposed by different enterprises to become de-facto standards in order to tackle the issues of communication interoperability, as these protocols possess different messaging architecture it is able to integrate different protocols through a semantic gateway, Desai, Sheth and Anantharam (2015) presents a semantic gateway just like this, which provides translation between the widely used CoAP, MQTT and XMPP protocols. Messaging-protocol interoperability may also be referred to as semantic interoperability.

The data annotation-level interoperability consists of the raw data from heterogeneous sink nodes and sensors, which does not contain any semantic annotation and because of that requires manual input to build any practical applications. This interoperability issue stems from IoT applications being deployed by providers in a bottom-up fashion from sensors, gateways, services to applications, these providers control the raw data structures of the nodes which they design to aid their specific application on the upper levels (Aly, Khomh, Guéhéneuc, Washizaki and Yacout, 2019). Data annotation may also be referred to as syntax interoperability.

One solution presented by Aly, Khomh, Guéhéneuc, Washizaki and Yacout (2019) in their research on fragmentation in the IoT market, is to interoperate IoT through standardization, for that reason IoT standards have intrigued the research community giving its attention to the development of suitable standards to a very fragmented market. The standardization development is a key factor for a more accessible market in the future, not only to determine the best technical protocols, but also accelerate the spread of these IoT technologies (Aly, Khomh, Guéhéneuc, Washizaki and Yacout, 2019).

Konduru and Bharamagoudra (2017) presents what they consider are the main issues among interoperability and the interoperable challenges surrounding IoT, as a key function of IoT is communication compatibility and as such the IoT devices needs to follow the same common communication. The main issues listed by the researchers are the lack of resources, proprietary technologies, complexity, security and the heterogenous devices.

To further explain these issues a brief overview will be given on each issue, in the reasoning of Konduru and Bharamagoudra (2017) starting with the lack of resources which stems towards the lack of joint development and open application programming interface (API) development, to accomplish the use of a common way for monitoring layer for sensors and devices although open development regarding security opens for more issues.

Whereas interoperability issues within proprietary technologies stems from the vendor-lock approach many software giants try to achieve, to extract market edge over the consumers compared to their competitors (Konduru and Bharamagoudra, 2017).

Resulting from the previous two statements on interoperability issues is the complexity, which stems from the lack of common patterns between IoT technologies and as such would require a common management system layer (API) to resolve the issues towards interoperability (Konduru and Bharamagoudra, 2017).

As for security, it also conflicts with interoperability as the increasing number of devices and users integrated in different levels of accessibility, it becomes increasingly complex and besides that, adapting interoperable communication between the devices opens for even more complexity, consequently security communication is a hurdle interoperability (Konduru and Bharamagoudra, 2017).

Lastly, heterogenous devices as mentioned earlier, are devices which has various ways of communicating data which may conflict with neighboring devices various ways of communicating data and as such does not possess a common standard to decipher data between devices (Konduru and Bharamagoudra, 2017).

Konduru and Bharamagoudr (2017) also presents purposed solutions towards interoperability within IoT in their conference paper, for each of the main interoperable issues discussed above. As for the lack of resources the purposed promising solution is a common monitoring layer for APIs and funding from organizations and governments. Whereas for the proprietary technology issues the purposed solution is to bring device manufacturers to a common standard to allow interoperability between devices and as for the complexity issue the purposed promising solution is developing a common API that is more simplified than what is currently offered. Moreover, the solution to the security interoperable issue also fits under a common standard, to adapt standard platform and data format so that security can be enhanced between stakeholders and lastly the purposed promised solution to heterogenous devices by Konduru and Bharamagoudr (2017) is following the previous trend as to define a common standard in development of device platforms. A standard to follow within development solves most of the main issues although it cannot by post-facto applied and as such is not as relevant to this current study.

Samuel (2016) word interoperability as the prime concern within smart home networks, as the common consumer needs an accessible method of connection, easy-to-connect and easy-to-use devices. As devices used within smart homes are made from a spectrum of different manufacturers and vendors, the type of communication also differentiates between the vendors whereas they still need to interoperate communication to achieve joint tasking.

Mentioned by Samuel (2016) is also the success of Wi-Fi, which in accordance to him is due to the remarkable efforts put into the technology and it's interoperability by the Wi-Fi alliance, even if the technicality of the technology is interlocked by its own specifications the technology is widely used in a broad range of devices and in the end offers good interoperability, down-side being the energy requirement which is far higher than many IoT-based protocols.

As a summary, interoperability within smart homes and IoT comes at several layers and not just the technical aspect of communication such as radio frequency or another medium, the challenges towards integrating smart homes and IoT are several spanning from security capabilities, vendor-locks, and the lack of a common API (Konduru and Bharamagoudra, 2017). The ultimate goal being for devices and communication to function in an reliable and predictable fashion.

2.2 Smart Homes

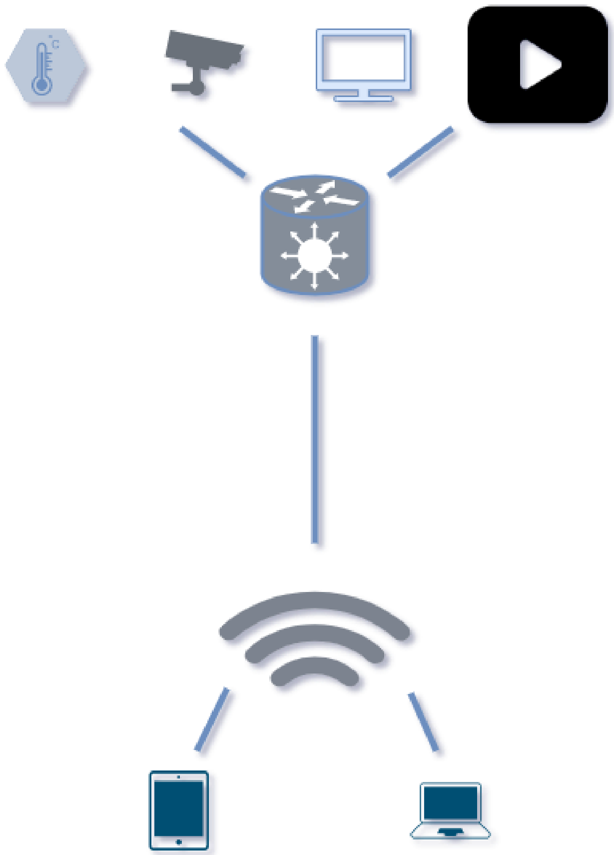

Figure 1. Example of smart home topology

As worded by Waleed, Abduldaim, Hasan and Mohaisin (2018) The Smart homes can be defined as living environments supplied with advanced intelligent technologies that anticipate and respond according to the requirements of the home residents.

Waleed, Abduldaim, Hasan and Mohaisin (2018) mentions three different main purposes of the smart home which is, providing comfort, improving security, and reducing energy consumptions. To provide all these purposes the networking within the smart home applications needs to be seamless with a flexible remote-control system, reachable by multiple points and devices by the end user.

The typical smart home consists of sensors and endpoints connected through a gateway or controller, which is accessible wirelessly to the end-user by their smartphone or tablet.

Items and devices within the common smart home includes TV, air conditioners, refrigerators, washers, door locks, IP Cameras, lightning, ovens, and sensors. Whereas sensors have a lot of different use cases within the smart home, including environmental, automation, monitoring and security (Kim et al. 2014).

2.3 Central concepts – Frameworks & Protocols

Here the central concept surrounding the current studies topics are presented and explained. Spanning from frameworks, protocols, and standards regarding interoperability and wireless communication within the smart home as well as the OSI model (2.3.1), to reference which layer of communication something relates to, such as a communicative protocol.

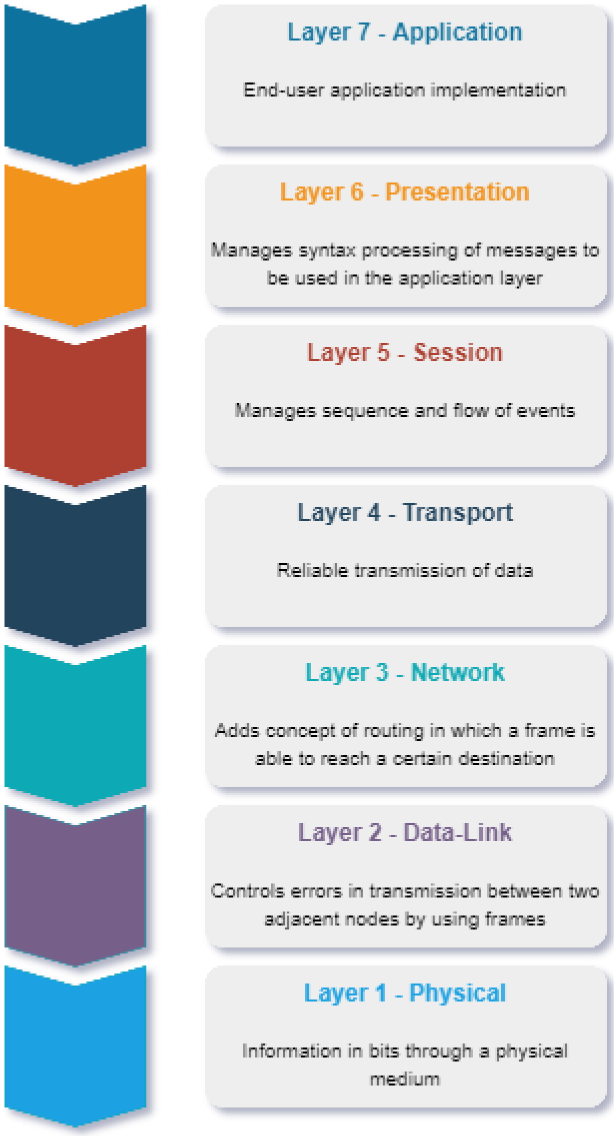

Figure 2. OSI Model

2.3.1 The OSI Model

The OSI model is a cornerstone of data communication defined by the ISO standard number ISO/IEC 7498 and whereas all the wireless protocols within the smart home utilize it in different extensions, it is an important part of understanding the central concepts of the presented materials. (ISO/IEC 7498-1:1994, 1994) Most of the IoT communicative networking standards and -protocols do not define anything beyond the first couple of levels, as for example the IEEE 802.11 standard only defines technologies at the first two, physical and data-link layers (Coleman and Westcott, 2018, pp. 67 - 74). Whereas in this scenario, the focus lies on the lower levels of the OSI model, to provide answers to technical & networking protocol interoperability solutions, this lower segment is labelled technological interoperability by Kotstein and Decker (2019).

2.3.2 Bluetooth

Bluetooth is an open wireless technology operating at the free ISM (industrial, Scientific & Medical) band of 2.4GHz. It operates in a point-to-point fashion and utilizes frequency-hopping spread spectrum with capabilities of changing frequency 1600 times a second between the 79 available channels which uses a 1 MHz spacing (Kumar and Gupta, 2015; Bluetooth Radio Versions | Bluetooth® Technology Website, 2021).

<u>Technical details of Bluetooth</u>

Frequency band:	2.4GHz ISM Band (2.402 – 2.480 GHz Utilized)
Channels:	79 channels with 1 MHz spacing
Channel usage:	Frequency-Hopping Spread Spectrum (FHSS)
Modulation:	GFSK, π/4 DQPSK, 8DPSK
Power consumption:	1 Watt
Data rate:	1 Mb/s to 3 Mb/s
Max TX Power:	Class 1: 100mW (+20 dBm)
Topology:	Point-to-point
Range:	5 m - 100 m

2.3.3 Bluetooth Low Energy

Bluetooth Low Energy (BLE) is a low energy power saving communication technology for Bluetooth and is aimed at low powered devices such as sensors. However, it does not maintain the data rate which classic Bluetooth can achieve (Kajikawa, Minami, Kohno and Kakuda, 2016; Bluetooth Radio Versions | Bluetooth® Technology Website, 2021).

<u>Technical details of BLE</u>

Frequency band:	2.4GHz ISM Band (2.402 – 2.480 GHz Utilized)
Channels:	40 channels with 2 MHz spacing
Channel usage:	Frequency-Hopping Spread Spectrum (FHSS)
Modulation:	GSFK
Power consumption:	0.01 to 0.5 Watt
Data rate:	125 to 2000 Kb/s
Max TX Power:	Class 1: 100mW (+20 dBm)
Topology:	Point-to-point, Mesh & Star
Range:	50 m

2.3.4 ZigBee

ZigBee is a low cost, low power, low data rate and low delay characteristics protocol which is widely used within wireless sensor network communications. The name ZigBee comes from honeybees zigzagging characteristics as it represents the mesh type communication. ZigBee utilizes the physical and data link layer of the OSI model (Ramya, Shanmugaraj and Prabakaran, 2011; Zigbee - Zigbee Alliance, 2021; Courreges et al., 2016; Marksteiner, Exposito Jimenez, Valiant and H. Zeiner, 2017).

<u>Technical details of ZigBee</u>

Frequency band:	913 MHz, 868 MHz & 2.4 GHz (ISM band)
Channels:	16-channels (2 MHz wide)
Channel usage:	DSSS
Modulation:	BPSK & O-QPSK
Power consumption:	Typical 1 mW or less
Data rate:	20 Kbit/s (913MHz & 868MHz) & 250 Kbit/s (2.4GHz)
Max TX Power:	20 mW
Topology:	Star, Tree & Mesh
Range:	< 100 m

2.3.5 Z-Wave

Z-Wave is a competing protocol in the smart home market owned by Sigma Designs. It is a low power protocol only targeted for home automation, the Z-Wave network uses a protocol specific central controller to manage all the devices in use, as it has no inherent possibility to communicate with other protocols. Z-Wave covers four levels in the OSI model, namely the physical, data link, network, and the transport layer (Linh An and Kim, 2018; Z-Wave Mesh Network Protocol Specification - Silicon Labs, 2021; Marksteiner, Exposito Jimenez, Valiant and Zeiner, 2017).

Technical details of Z-Wave

Frequency band:	865.2MHz to 926MHz (Region based)
Modulation:	FSK
Data rate:	100 Kb/s
Topology:	Mesh
Range:	< 30 m

2.3.6 Wi-Fi

Wi-Fi is defined by a family of 802.11 standards, it has grown to become the most popular wireless technology for data transmission within the home. Wi-Fi has had such an on-going evolution as has its popularity within the market, which indicates that data rate speeds will continue to grow as they have in the past years, from legacy 2 Mbps of IEEE 802.11-1997 to almost 10 Gbps in the latest 802.11ax. With these transfer speeds come great downsides of power consumption capabilities compared to other smart home communications (Khorov,Levitsky and Akyildiz, 2020; Different Wi-Fi Protocols and Data Rates, 2020).

Technical details of Wi-Fi

Frequency band:	2.4GHz, 5.0GHz or 60 GHz
Channels:	14 (2.4GHz) & 196 (5.0GHz)
Channel usage:	OFDM, DSSS or FHSS
Modulation:	BPSK, QPSK or 16-, 64-QAM
Topology:	Star & Point-to-Point (P2P).
Range:	30 m - 200 m

2.3.7 KNX-RF

The KNX-RF standard is typically used in home automation and building management with capabilities in areas such as energy management, lighting, shutters, heating, air conditioning controls, security, and remote access. Like many other home automation standards, it is a low-power technology providing a long-lasting lifetime of battery devices. In the OSI model KNX-RF covers the data link, network, and transport layer (Oudji, Courreges, Paillard and Meghdadi, 2016; Courreges et al., 2016; Marksteiner, Exposito Jimenez, Valiant and Zeiner, 2017).

Technical details of KNX-RF

Frequency band:	868.3 MHz or 433 MHz
Channels:	2 (Multi Slow) or 3 (Multi Fast)
Modulation:	FSK
Data rate:	16.4 kbit/s
Max TX Power:	25 mW
Topology:	Star, Mesh & Point-To-Point/Line (P2P)
Range:	~50 m

2.3.8 EnOcean

EnOcean (EO) is a low-power wireless communication standard which is typically used for automation in both office and home environments. It aims to be more energy efficient than competing standards using its energy harvesting functionality, self-sufficient by the use of energy harvesting items such as a solar panel, a thermogenerator or an electromechanical generator (Arcari et al., 2017). In the OSI model EnOcean covers physical, data Link, and the network layers, the EnOcean alliance also provides an application layer functionality called EnOcean Equipment Profiles (EEP), this is to provide interoperability between suppliers within the standard (Marksteiner, Exposito Jimenez, Valiant and Zeiner, 2017; EnOcean Alliance, Technical Specifications, 2021; Courreges et al., 2016).

<u>Technical details of EnOcean</u>

Frequency band:	2.4GHz, 928.35MHz, 902MHz, 868.3MHz & 315MHz
Channels:	1
Modulation:	ASK (315 MHz) & FSK (902 MHz & 928.35 MHz)
Data rate:	125 Kb/s
Max TX Power:	20 mW
Topology:	Star & Mesh
Range:	30 m - 300 m

2.3.9 Thread

Thread is an IPv6 based protocol utilizing the 6LoWPAN standard, established in 2014. Thread tackles the interoperability issue by implementing IP-based communication and does not set a standard for the application level, to avoid locking the supplier to a specific solution. The IPv6 communication allows for seamless connectivity with other IP capable devices such as mobile devices. The Thread protocol covers layer three and four of the OSI model and uses the IEEE 802.15.4 standard in the missing layer one and two (Lan, Pang, Fischione, Liu, Taherkordi and Eliassen, 2019; Marksteiner, Exposito Jimenez, Valiant and Zeiner, 2017).

<u>Technical details of Thread</u>

Frequency band:	2.4 GHz (ISM band)
Channels:	16-channels (2 MHz wide)
Channel usage:	DSSS
Modulation:	QPSK
Data rate:	250 Kb/s
Topology:	Mesh

2.3.10 LoRa (LoRaWAN)

The idea of LoRa is to utilize a unique modulation technique chirp spread spectrum which provides very long range communication possibilities, LoRa is adaptable far beyond the smart home and has appliances in all of the IoT spectrum, with it being an especially long range communicative protocol, efficient, and strongly mesh based topology characteristics makes it an attractive solution in the IoT field, however it is not yet commonly adapted within the smart home (LoRaWAN™ What is it?, 2015).

Technical details of LoRa

Frequency band:	867 - 928 MHz
Channels:	10 in Europe & 64 + 8 + 8 in North America
Modulation:	SS Chirp
Data rate:	290 b/s - 50 Kb/s
Topology:	Mesh

2.3.11 6LowPAN

6LowPan, an acronym for IPv6 over Low -Power Wireless Personal Area Networks, is a protocol standardized by the IETF (Internet Engineering Task Force), designed by the 6LowPAN group to adapt energy efficient IPv6 routing over loosely links, as it is designed in the favor of low-powered devices it is limited in processing capabilities. IPv6 packets can be sent and received over the IEEE 802.15.4 base networks. It provides interoperability functionalities in the form of an adaptation layer, adapting packet sizes over what the traditional IP networks and IEEE 802.15.4 networks (Aly, Khomh, Guéhéneuc, Washizaki, Yacout, 2019).

2.3.12 M2M (Machine-to-Machine)

M2M is an abbreviation for machine-to-machine, which is direct communication from one device to another without the use of a communication channel, for instance a gateway. This abbreviation is heavily used within the research for interoperability and standardization within smart homes, as one of the key issues is enabling direct communication from one device to another without the use of a channel of communication, but instead interoperating the different communication protocols the devices may use, to enable direct communication between the heterogenous devices, M2M (Aly, Khomh, Guéhéneuc, Washizaki, Yacout, 2019).

2.3.13 OneM2M

OneM2M is a global standard initiative for machine-to-machine communications within IoT, the main goal is to define a framework that support interoperable applications and services in different categories, such as healthcare, smart cities, and homes. OneM2M is defined by a middleware service layer, providing an access independent view of end-to-end services. With the service layer in place, developers can focus on developing more and more business applications rather than on interoperability issues. With a suitable framework and service layer in place, development can focus on application development rather than having to lay comprehensive amount of work on solving interoperability issues. The second release in August 2016 also adapted major focuses on semantic interoperability (Singh, Dwarakanath, Haribabu and Babu, 2017).

2.3.14 MQTT

Message Queuing Telemetry Transport (MQTT) is a lightweight connectivity protocol invented and developed by IBM; the connectivity protocol is based upon TCP/IP (MQTT Version 5.0 OASIS Standard, 2019).

MQTT uses a publish/subscribe communication technique designed around a central broker, this broker act as a data forwarder to clients, clients which in turn connects to the broker and either subscribe to data or publishes it, on specific topics of interest (Kim, Choi, and Rhee, 2015). The topics are based upon the device's description elements, such as home environmental sensors (Kim, Choi, and Rhee, 2015).

MQTT also comes with support of quality of Service (QoS) and due to the lightweight nature of MQTT makes it adaptable by very efficient and low-powered devices, therefore it is a popular choice of a uniform communication protocol within IoT, and smart homes being just one of the adaptable use cases (MQTT Version 5.0 OASIS Standard, 2019; Kim, Choi, and Rhee, 2015).

A key feature of MQTT in this research is the functionality of the asymmetric communication protocol characteristics it withholds, in an ability to accept different kind of communicative protocols and as such is viewed as a one-to-many protocol. As such it's able to interoperate different kinds of networking communicative protocols in the lower OSI layers, even protocols which does not utilize IP for part of layer three in the OSI model (MQTT Version 5.0 OASIS Standard, 2019; Kim, Choi, and Rhee, 2015).

2.3.15 CoAP

The constrained application protocol (CoAP) can also be regarded as a lightweight publication or subscribe event-based method such as MQTT, whereas CoAP is an open-standard based communication protocol meaning the efforts in standardization is open to anyone for free, without royalties (Lei Hang, 2017; Shelby, Hartke and Bormann, 2014). The core focus of CoAP is being a lightweight communicative application protocol and assist resource constrained devices within IoT, based around the same principles as HTTP it makes it easy to implement and use (Lei Hang, 2017). CoAP is IP based and enables it to integrate with current IP based infrastructure as well as interconnecting IoT devices with HTTP and the RESTful web through simple proxies (Lei Hang, 2017; Shelby, Hartke and Bormann, 2014).

2.3.16 AllJoyn (OCF)

The AllJoyn framework which was in 2016 merged by the Open Connectivity Foundation (OCF), the framework which is a collaborative open-source framework was developed to adapt devices to engage them to discover other devices within the same network and enable the possibility of them to communicate without consideration of the physical media (Sowah et al, 2018).

Inherently the AllJoyn framework has only support for the IP stack communicative protocols such as Wi-Fi and Ethernet LAN, and if different communicative IP stack protocols are interconnected together in an interconnecting node that has support for the respective interfaces, they may communicate with another. Whereas with the "*AllJoyn Device System Bridge*" developed by Microsoft, adds extensible properties to handle protocols outside of the IP-stack spectrum, for instance Bluetooth, Z-wave, ZigBee, and other media (Sowah et al, 2018).

2.3.17 XMPP

The Extensible Messaging and Presence Protocol (XMPP) is a protocol standard for instant messaging, it allows for possibilities to adapt authentication, access control and privacy which can be especially attractive to IoT, and the ability for end-to-end communications. It connects clients and servers using the XML called *stanza,* the main functionality of the XMPP protocol is to send client-server or vice versa text-based communication, based upon keeping the intelligence at the server side instead of the endpoints, although the increased overhead by heavily text-based messages increases the network load (Masek et al, 2016).

2.3.18 REST

REST, abbreviation for representational state transfer, is commonly used within smart home frameworks as an interactive method to create applications through web services using HTTP (Kim et al. 2014). Consequently, it is not part of the lower layers of the OSI model as it is application-based and utilizes HTTP to communicate data, however it is often used as a part of frameworks to achieve full interoperability across all layers (Kim et al. 2014). This is accomplished by forwarding the application data retrieved from a smart home to cloud-based web services, which the end user or customer then easily can connect too with various devices within the smart home using this central web-based controller (Kim et al. 2014).

2.3.19 AMQP

AMQP, abbreviation for Advanced Message Queuing Protocol is a lightweight extensible messaging protocol specifically designed for M2M messaging. The protocol mainly focusses on adapting interoperability in corporate environments. Like MQTT, AMQP supports both request-response and publish-subscribe based communication at the application layer. Tackling the interoperability issues through the message-oriented middleware (Al-Masri, et al. 2020).

2.3.20 SIP

Short for Session Initiation Protocol, is a text-based protocol which revolves around request and response, like the HTTP-based communicative protocol counter parts, SIP is working through UDP, TCP and SCTP (Masek et al, 2016). Proposed by IETF (Internet Engineering Task Force) the SIP is as an application layer-based control protocol, it does not interfere with the lower layered technical protocols and accomplishes to provide a functioning point-to-point or multi participant multimedia session and does so without defining any specific session type, therefore any type of data stream can be transmitted (Zhang, Ji, Liu and Song, 2018). As SIP is suitable for IoT environments, it does have use cases in smart home architectures, consequently it can be seen used in several articles (Zhang, Ji, Liu and Song, 2018; Masek et al, 2016).

2.3.21 DDS

Data Distribution Service (DDS) is another publish and subscribe based protocol for real time communication for adaptation in M2M environments, with the support for Quality of Service (QOS). In short terms, a Publisher sends required data and subscriber receives data and transfer it to respective application (Masek et al, 2016). DDS is developed by Object Management Group (OMG).

2.3.22 Weave (OpenWeave)

Weave, by Google is a framework that features communication between cloud, devices, and phones. By doing so it enhances the user experience across mobile devices and the web. Supports IEEE 802.15.4 transport communications and provide secure communication adaptation. It was later released as an opensource project in 2017 named OpenWeave. Labeled as an easy to use and versatile framework, as an example opening communication from device-to-device, device-to-service, device-to-mobile/Phone/PC (Konduru and Bharamagoudra, 2017; openweave/openweave-core, 2021).

2.3.23 HomeKit

HomeKit is a framework by Apple, provides the consumer with a centralized solution for HomeKit-enabled proprietary devices within the Apple spectrum of the HomeKit framework, these devices can be things such as iPhone, iPad & Apple Watch. Consequencely it only provides interoperability within its own environment, an easy adaptable solution but does not provide interoperability across platforms and through traditional devices (Vongchumyen, Torthitithum, Khamsopa and Watanachaturaporn, 2019; Konduru and Bharamagoudra, 2017).

2.3.24 IoTivity (OCF)

IoTivity is an opensource framework, implemented and sponsored by Open Connectivity Foundation (OCF) into their standards of providing easy and secure communications within IoT. The IoTivity project was purposed to accelerate the work and bring together the opensource community towards the development of a framework to connect IoT (About | IoTivity, 2021).

2.3.25 UPnP (OCF)

The UPnP technology target home networks, proximity networks and small office networks. Used to enable communication between any two devices, by using a control device within the network. UPnP tries to adapt itself without being dependent on other technologies such as operating systems, programming language and network technology. Consequently, it withholds some interoperable favoring characteristics as it is open for adaptation in multiple technological environments and media independence. Built around TCP/IP, HTTP and XML communication. Provides end user with user interface control as well as programmatic control. The UPnP technology is since 2016 asserted by OCF (OCF - UPnP Standards & Architecture, 2021).

2.3.26 SOAP

Simple object access protocol (SOAP) is an extensible communication protocol used for web-based communication through mainly HTTP but also through FTP (File Transfer Protocol) or SMTP (Simple Mail Transfer Protocol). By utilizing XML through HTTP, it is adaptable by both new and traditional device systems, similar to XMPP discussed earlier, with an accessible of programming language variety (Mohamed and Zeki, 2017).

2.3.27 OSGi

OSGi developed by OSGi Alliance and formerly known as Open Service Gateway Initiative is a flexible and functional service gateway. The OSGi specification defines a Java framework for developing and deploying modular applications and libraries. The gateway standard enables for various home devices to interconnect, the OSGi architecture is bundled as a service of packaged Java class and data. Whereas this adapts interoperability towards a centric gateway, it does not enable direct device-to-device communication over heterogenous networks which is an attractable characteristic in a sensor/mesh heavy network (Kato, Matsubara, Yoshida and Ishikawa, 2016).

2.3.28 OpenHAB

OpenHAB is an open framework that allows for remote control over multiple communications protocols for their co-existence, based upon Java this opensource framework operates on any platform operable by Java Virtual Machine, like mobile devices and computers. In this framework the physical devices and services are referred to as "Things" and the things provide their functions in one or multiple "Channels", whereas the Things and Channels are the physical layers, the abstraction of the functionalities are referred to as "Items", which within is operated by the user to interact and adapt the automation process of OpenHAB (Parocha and Macabebe, 2019).

2.3.29 PUCC

P2P Universal Computing Consortium (PUCC) withholds a consortium of protocols developed by PUCC, their goal is to provide extensible and scalable protocols for various tasks and devices spanning from mobile phones, home appliances, sensors, and computers; And at the same time maintain existing designs and architectures of existing technologies and networks. PUCC features an overlay network design, P2P communication, and ad-hoc networking as well as XML communication protocol for communication between devices within the metadata (Kato, Matsubara, Yoshida and Ishikawa, 2016).

2.3.30 Universal Remote Console

Universal Remote Console (URC) is a framework designed for personal and exchangeable user interfaces, consequently the goal is to enable user control in a centralized fashion to any device or service with an adaptable user interface to their best needs. URC uses an HTTP Protocol as a middleware solution, through a controller called Universal Console Hub (UCH) (Smirek, Zimmermann and Beigl, 2016).

2.3.31 Eclipse Smart Home

The Eclipse Smart Home (ESH) is a flexible and modular framework for smart home solutions. ESH provide flexibility in terms of co-existence of heterogenous fragmented protocols, ESH aims to define a common communication protocol that can cope with the heterogenous devices. OpenHAB describe the basis for ESH and as such it shares the characteristics of the structure, the physical devices and services are referred to as "Things" and the Things provide their functions in one or multiple "Channels", whereas the Things and Channels are the physical layers, the abstraction of the functionalities are referred to as "Items", which within is operated by the user to interact and adapt the automation process, same as the previous discussed OpenHAB. In short terms, Eclipse is a development of OpenHAB moved under the Eclipse Foundation (Smirek, Zimmermann and Beigl, 2016).

2.3.32 SDN

Software-Defined-Networking (SDN) is an architectural approach which evolves around maintaining dynamic, manageable, and adaptable communication across layers, decoupling networks, and making network control directly programmable giving an agile and centralized administration as well as a vendor-neutral capable network controller though software defined instructions, making it a suitable architecture for a fragmented network (Software-Defined Networking (SDN) Definition - Open Networking Foundation, 2021).

2.3.33 Insteon

Insteon is a protocol which functions on two physical mediums, both through radio frequency (915 MHz) and through the powerline (132KHz). Insteon is a fully fledged mesh topology protocol which advertise brand interoperability and physical interoperability without the use of a centric router or administrative hierarchy. Insteon is specifically designed for home monitor and controlling (Technology — Insteon, 2020).

3 Problem

The problem arises when without interoperability, the smart devices cannot work in symbiosis with each other (Banerjee, Sufyanf, Nayel and Sagar, 2018, p. 78). Which may result in scenarios such as an end-user not being able to control the heat by the temperature thermostat utilizing automation, if the devices such as temperature sensors or gateway hubs use different proprietary protocols to communicate (Farooq, Wheelock and Pesch, 2020), which in turn may make smart homes less interoperable and harder for the consumer to apply a centralized solution too (Banerjee et al. 2018).

Interoperability issues come at several communicative layers, spanning from the physical layer, which is being radio frequency waves in the case of wireless smart home solutions which directly corresponds to the first layer in the OSI model, up all the way to the application layer which the end-user utilizes to interact with the complete solution.

In the current smart home market, main academic focus has been at the first communicative layers, typically covering layer one to three, or four in the OSI model, as the range of heterogeneous proprietary protocols is broad spanning from several different technologies (Farooq, Wheelock and Pesch, 2020).

Heterogeneous devices within the smart home, even if working seemingly fine may assert into conflicting results as they possess no knowledge of other surrounding devices, as such their actions can conflict each other. An example would be temperature sensors unknowing of each other's existence can result in an inefficient home environment by triggering the heating on and off inconsistently (Mohamed et al. 2018).

This stems from the way the communicative protocol's function, as for example Z-Wave operates at the frequency band 868.42 MHz in Europe or 908.42 MHz in North America while Bluetooth on the other hand operates at the crowded 2.4GHz frequency band. Every protocol provides its unique set of characteristics, Bluetooth is particularly good for high data rate bandwidth transmission, while Z-wave is a lot more bandwidth restricted but a lot more energy efficient. The topology differs as well between available protocols, some typically utilizes mesh-networking such as Z-wave and Zigbee whereas standard Bluetooth utilizes point-to-point communication. Taking the unique characteristics of each protocol into consideration, standardizing to one single communicative protocol, and neglecting all others is not feasible for an optimal smart home today, as some frameworks and protocols have better use-cases and implementation for specific tasks than others. As such an interoperable framework to integrate all the heterogeneous devices within the smart home is a key focus (Bluetooth Radio Versions | Bluetooth® Technology Website, 2021; Zigbee - Zigbee Alliance, 2021; Z-Wave Mesh Network Protocol Specification - Silicon Labs, 2021; Linh An and Kim, 2018).

3.1 Research Question

"Which options towards wireless communication interoperability are available for smart homes?". Set out to evaluate different smart home communicative protocols and their solution for tackling interoperability as well as possible frameworks and architectures capable of achieving interoperability within a heterogeneous environment.

Questioning not only a specific communicative protocol's way of handling interoperability, but all the solutions towards interoperability within the smart home environment, as to provide answers to smart home adaptation in terms of communication. This does neglect any other interoperable issues which may arise in the smart home outside of technical and networking interoperability within communication, for example specific semantic and data-syntax miscommunications interoperable issues in the higher layers of the OSI model, however it does not neglect solutions which indirectly provides interoperable communication to the lower technical- and networking layers through higher layer application-based communication, which a lot of semantic software-based solutions in fact does (Tooba, Muhammad and Martinez-Enriquez, 2018).

The current study only focuses on the technical and networking communication aspect; To answer how it can be accomplished. However surrounding aspects may be included if they hold relevance to answering the original question.

3.2 Motivation

Whereas the problem area is known in the academic field, it does lack work that has compiled the current research surrounding how networking interoperability within smart homes can be accomplished, research that presents frameworks and solutions to the problem of network protocol interoperability.

The idea is to fill the void of compiled research surrounding the issue, through compiling current solutions by defining the positives and negatives surrounding each of the different communicative protocols and of the frameworks and gateways available used to adapt heterogeneous devices and apply post-facto interoperability to the communication. This would aid and guide the choices of interoperability implementation within the smart home environment to other researchers or end-users by providing an informative objective take on available technologies, frameworks, and their solutions.

Applying interoperable solutions to heterogenous devices within the smart home may in most cases also maintain the most energy efficient communication method for each heterogenous end-device. The characteristic of different networking protocols within the smart home differs, as presented earlier in *chapter 2.3*. Consequently, some communicative protocols are more suitable than other for certain devices and applications, which further increase motivational reasons to adapt different communication methods by increased efficiency (Samuel, 2016; Yang, Poellabauer, Mitra, Rao and Neubecker, 2017).

3.3 Research Goal

The main goal of this work is to conduct a literature review on assessing how technical and networking protocol interoperability could be achieved in wireless smart homes environments, by gathering a summary of current work in the field surrounding the interoperability issue within smart homes specifically, thus, gathering relevant communicative protocols and frameworks used by other researchers towards accomplishing interoperability within the smart home. However, this current study does not set out to define new ways in which interoperability can be accomplished, but to extract results from relevant research within the area to gather an objective take on the interoperability solutions to wireless communication within the home. This could be used by future work, researchers, and experienced end-users on choosing an adaptable way to overcome heterogeneous devices in their specific environment and layer of communication, to avoid resource conflicts resulting in energy inefficiency and achieving ease of use, management, and accessibility in the smart home environment (Mohamed et al. 2018).

4 Methodology

The proposed methodology is a systematic literature review, as the research area is of constant ongoing development it has a lot of documentation, relevant academic work and market attraction surrounding it, which makes a literature review for a good choice, to summarize all the existing work within the field as it is highly saturated and adaptable to the research question, which objective is to question how network protocol interoperability can be accomplished in the smart home, as a summary of available solutions is needed to answer the question in an unbiased way and according to Kitchenham (2004), which describes summary as a primary reason to undertake a literature review.

Whereas also the research goal is connected to reviewing current technical and network protocol interoperability solutions, a literature review makes for a good basis on assessing the relevant information in high detail, to form conclusions surrounding the research question.

Whereas the systematic literature review approach is used to extract relevant data surrounding the research question and filter out any irrelevance using predefined criterion, checklists, and search strings. A thematic coding approach is set out as a methodology to analyse the results gathered through the systematic process, thematic coding being an excellent and flexible approach to analyse qualitative data in a literature study according to Braun & Clarke (2006). A method of analysis for identifying, analysing, and reporting patterns and themes within data (Braun & Clarke, 2006), the approach of analysis is widely used but does not have an exact template of agreement on how operation should be executed, as a consequence it is vital that the approach of analysis used is as transparent as possible by providing clarity around the process and practice of the method (Braun & Clarke, 2006), see *chapter 4.6* for further details of the thematic coding approach used in this research.

4.1 Search string

A systematic literature review must be accompanied by a predefined search strategy in accordance with Kitchenham's (2004) work, in consequence by design a predefined search string used to assess the scientific articles within the research area, using inclusion and exclusion criteria to filter out the search result with predefined rulesets, with the goal of an unbiased and objective result extraction.

The search string is adapted through a lot of trial and error and rigorous testing using multiple search strings to conclude the most relevant dense hits but still not excluding any articles which may be of relevance, the search string is evolved from multiple network protocol specific searches, which the first ten or more pages then are briefly analysed to gather a sample of relevance and reference (Kitchenham, 2004). These multiple search strings were then interjoined by "AND" and "OR" statements to provide one search string to cover the whole spectrum of technical and networking protocols with connections to the research question and interoperability, found during the background research. This one search string is then applied to Google Scholar to create a larger picture of the available documentation in the field and their databases hosting the material.

As Google Scholar is a tool to search academic publications (Noruzi, 2005), it is in this case primarily used to find other sources of relevant material to search, such as databases, and not direct data extraction.

The specific purpose of Google Scholar in this case, is to find relevant academic databases; For example, in case a database is found which host new relevant material to the research question according to the predefined criteria, the database will then also be considered for searching with a newly adapted search strings through the previously mentioned iteration process to conclude a relevant dense result on that specific database, as the databases search functionality usually varies. Consequently, as Google Scholar has a thousand result limitation on searches, a highly dense and well published field as IoT easily overshoot that search result value making it a lot less attractive in this specific scenario, as a systematic literature review strives to find and review every relevant literature (Kitchenham, 2004). This resulted in that the first thousand search hits provided by Google Scholar in this scenario is solely used to find suitable databases. Accomplished by applying the criteria from *chapter 4.2* and the checklist from *chapter 4.3* to the search hits provided by Google Scholar sorted by their relevance, whereas when a relevant article is found from the search hits, the database hosting the relevant article is then instead saved and a finalized search string is specified for that database and the material found on that specific database through Google Scholar should again become a result from the newly saved databases instead.

The Google Scholar search string, used to find relevant academic databases and archives which hosts material relevant to the field of the research question:

```
"Smart Home" AND "IoT" AND "Interoperability" AND "Protocol" AND "Framework" AND "KNX-RF"
OR "EnOcean" OR "Wi-Fi" OR "Bluetooth" OR "ZigBee" OR "Z-Wave" OR "Thread"
```

4.2 Criteria

Inclusion and exclusion criteria are used to filter out irrelevant articles to the research question and maintain anything with relevance, to find anything related to network communication protocols within smart homes surrounding the interoperable issue. These criteria are an essential part of conducting a systematic review (Kitchenham, 2004). The criteria are then applied to all articles found using the previously mentioned search string methodology, on all the discovered databases and Google Scholar.

Inclusion criteria

- Articles written in either English or Swedish.
- The article must include context to smart homes, either as a core subject or relations to the researchers' core subject.
- The article must include either takes on the communicative protocols used within the smart home or the interoperability/heterogenous issues as a subject.

Exclusion criteria

- The article is not locked by payment or other forms of accessibility locks outside of what is offered by the University of Skövde.

- Articles that are not peer-review and as such lack an academic standard.
- Articles and journals which are based upon expired or abandoned networking protocols are excluded.

The criteria do not mention any time spans as some of the protocols stem from 2000s and as such may still hold relevant information. The search string itself does for the most part neglect any older irrelevant article by the terms it includes as they are relevant to what is being worked on today and less so anything pre 21st century.

IEEE-Xplore is heavily saturated by articles and journals which are locked behind payment or accessible accounts on the database platform, this exclusion *"The article is not locked by payment or other forms of accessibility locks outside of what is offered by the University of Skövde"* is disregarded on this platform as the University of Skövde offers access to this website. Whereas articles found using Google Scholar must be manually filtered through the exclusion criteria by their accessibility and availability.

4.3 Checklist

As the term "*The article must include context to smart homes, either as a core subject or relations to the researchers' core subject*" in the inclusion criteria may seem vague, an approach was set out to create a checklist (Kitchenham, 2004).

So that the research remains unbiased and not tampered by results that are guided by an unwanted subjective mindset. This is done by examining any article that does not mention "smart home" in the title and see if that article mentions "smart home" anywhere beside the abstract, if it does it is included and if it does not mention "smart home" outside of the abstract it is excluded from the results.

This is done as the research is on a set timeframe, spanning through the spring term 2021. Although if results correlated to the inclusion criteria are found while applying this filter, the filter will be neglected, to avoid excluding relevant material.

4.4 Data extraction

To provide further transparency and reduce the opportunity for bias, the exact process for extracting the data is also discussed (Kitchenham, 2004).

Data extraction is performed through the databases found using the predefined search string, inclusion- exclusion criteria and checklist discussed earlier in the methodology. All findings which are relevant through the above filters, search string, criteria and checklist are then saved in a list of direct links to the results.

When the list is fully saturated from all the filtered search hits, each item in the list is then read carefully in higher detail to reiterate and once again apply the inclusion criteria "*The article must include either takes on the communicative protocols used within the smart home or the interoperability/heterogenous issues as a subject.*" and the exclusion criteria "*Articles that are not peer-review and as such lack an academic standard. ".* This is done last, after all the other filters as it is higher risk of adding subjectivity in the mixture when applying these specific criterions and therefore it takes extra precaution when applying them through careful reading.

A three-step selection process is being used within the research; Being the first search hits, initial criteria application, and the last criteria reiteration. This is being done to guarantee relevance to the research area.

Data contents filled into these lists consists of:

- Name of the work.
- Hyperlink directed to the work.
- Referencing.

At this stage, thanks to the informative data list, duplicates are to be overviewed as the material stems from several databases it is likely that duplicates of the same article may arise.

4.5 Delimitations

This study will limit itself to IoT within the smart home environment specifically, neglecting industrial, city and building solutions, adaptable by knowledgeable end-users within the smart home environment or other researchers looking for an appropriate way in their environment to interoperate the smart homes communication.

Whereas for interoperability, the study will focus on the communicative technical and networking aspect and their heterogeneous characteristics towards each other, as such it neglects other interoperable issues. This will exclude interoperability issues on the application layer, semantic message-protocols, and data-annotation miscommunications between devices in the higher layers of the OSI model (Tooba, Muhammad and Martinez-Enriquez, 2018). However, in material where the solutions cover several layers of the OSI model, in which networking protocol heterogeneous issues are also solved, it will too be included. Networking protocols within the smart home usual covers the first four layers of the OSI model and is labelled technological interoperability by Kotstein and Decker (2019).

The literature review is limited to the databases presented by Google Scholar and IEEE-Xplore. As Google Scholar provide links to external sources, and these external sources or databases, will likely result in collision pairings which frequently occurred between IEEE-Xplore and Google Scholar during earlier stages, the reason why the search is limited by these two are also inherent of the time limitation this literature review has, which is spanning through the spring term of 2021 with a final deadline in June 2021. As for the reason why IEEE-Xplore is still chosen as a predefined separate database alongside Google Scholar, is the availability to students of the Univeristy of Skövde, which directly corresponds to one of the exclusion criteria "*The article is not locked by payment, outside of what is offered by the University of Skövde.*".

The search string is limited to the seven wireless networking protocols covered during the initial background research, which consists of, KNX-RF, EnOcean, Wi-Fi, Bluetooth, ZigBee, Z-Wave, Thread and LoRa. Based on the initial discoveries during the background documentation these were the common networking protocols used in smart homes or surrounding the problem area, covering enterprise solutions all the way to smaller adaptable consumer solutions. This however will not be limiting any result extraction through criteria, any additional wireless networking protocol discovered from the result may provide useful information regarding the research question and therefore is regarded in this current study.

4.6 Analyzing the results

With the extracted data from the systematic literature review methodology, the analysis approach is to apply thematic coding, a process of collecting data through sentences, statements, chapters, or complete articles, which hold relevance to the research question (Braun & Clarke, 2006).

The analysis methodology is widely used; however, it does not have clear guidelines on how in which it is accomplished through its process (Braun & Clarke, 2006). As such it is important to document on how the process of analysis is performed to maintain transparency and integrity of the research as Kitchenham (2004) explains, whereas Braun & Clarke (2006) word it as a good thematic analysis will make it transparent.

This is done by careful analysis of each extracted result, identifying the values relevant to answering the research question and theming them in corresponding areas defined by their solutions to accomplish interoperability within the smart home, for instance a complete framework, interoperability solutions within a certain networking protocol or a multi-aware gateway. Consequently, summarize these identified solutions in an organized manner presentable because of identified themes of the results solution to the research question of networking interoperability within the smart home (Braun & Clarke, 2006).

By utilizing this qualitative method, analyse and identify patterns and themes, accomplished by highlighting relevant sections, organize the findings in themes and summarize the identified themes.

4.7 Validity

A big validity issue with the research is the fast rate of market in which smart homes and IoT currently evolve, in consequence it increases the risk of the research being rapidly irrelevant within the near future (Aly et al., 2019). This also stems from the lack of standardization now, which is one of the reasons of the heterogenous market in a need for interoperability, the standardization of IoT is essential and expected to be much clearer soon according to several researchers (Aly et al., 2019), and therefore would potentially solve majority of the research question at hand.

As it is based upon a comprehensive systematic literature study which revolves around a vast amount of material, it does as such contradict any single- view or take by researchers' within and surrounding the object of the study, that being accomplished by using all the extracted data within the area and gathering multiple views from multiple sources on multiple solutions for a diversifying range on the research field, to strive for objectivity (Kitchenham, 2004).

The network protocols used within smart homes are often considered heterogenous by nature as the developers want to interlock consumers to their developed solutions and frameworks, therefore as this research takes these wireless networking protocols into consideration and their specifications, a lot of the data specification and documentation provided by the developers is very subjective to their own frameworks (IoT Delegate: Smart Home Framework for Heterogeneous IoT Service Collaboration, 2016). Consequently, careful consideration must be taken when reviewing vendor data and developer's specification publications to avoid the risk of objectifying subjective data presented by publishers pushing for vendor lock-in traps (Willocx, Bohé, Vossaert and Naessens, 2018).

The process of analysis is an extraordinarily complex process, going through this vast amount of material it does include a risk of subjectivity when applying the result and material in their specific categorization and theming. Therefore, to maintain transparency of the process the relevant documentation of results is incredibly important (Kitchenham, 2004).

5 Implementation of the literature review

The process in which how the methodology, described in detail through chapter four, is accomplished. Consequently, this is the process of which the studies material was collected and extracted as a base for the analyse and result chapter.

The basis of this process stems from the previous chapter four which describe the methodology in detail, search terms which were used here and specifically designed for the database in which it is used upon. These search strings came to surface from the earlier documentation of the background and from applying the methodology, as continued reading within the area increases insight within it and as such some keywords can be acknowledged in the process, keywords that were frequently used within this current research's field (Friberg, 2017), such as "Interoperability", "IoT", "Gateway" and "Framework". Even though the final search strings used are more open, they stem from the predefined search string and the words it contained, defined in the methodology chapter, to keep and maintain the integrity of the predefined search string strategy (Kitchenham, 2004).

However, one additional phrase was added to some of the searches, "Gateway", as it was commonly used to define as a term to interconnect heterogenous devices and achieve interoperability (Vargas and Salvador, 2016). The word was used mainly to avoid limitation of the search engines maximum result cap.

Hence, all the used search strings were as open as possible and therefore short, to avoid excluding any material. This increased the work demand during filtration but decreasing the chance of excluding relevant material, which is critical not to do in the process of a systematic literature review (Kitchenham, 2004), as it's key to take all of the relevant material into consideration and not miss any key detail or information in which could affect the analyse and result process (Kitchenham, 2004), therefore this was the main reason several databases were used and as short search strings as possible for the specific database, without reaching any result limitation, such as Google Scholars thousand search results limit discussed in *chapter 4.1*. Consequently, discovered during the process of the methodology the database *Semantic Scholar* also has a search result cap of a thousand results, just as Google Scholar, in which a longer search string was used, and the phrase "Gateway" was implemented.

5.1 Search of material

The scientific database IEEE-Xplore held the highest density result hits on Google Scholar by a large margin, as well access is provided by the University of Skövde to this platform, in result it does not conflict with the criteria "*The article is not locked by payment or other forms of accessibility locks outside of what is offered by the University of Skövde.*".

In conjunction with IEEE-Xplore the other academic databases, archives, and portals found and used are presented in the following *table 1*, with included hyper-links to respective website hosting the database/archive.

Database(s):
IEEE-Xplore
Eindhoven University of Technology research portal (TUE)
MDPI - Publisher of Open Access Journals
Aalto University: Aaltodoc
Chalmers Open Digital Repository
University of Stuttgart: OPUS
Jeju National University
Digitala Vetenskapliga Arkivet (DiVA)
Korea Science
ResearchGate
CORE
SAGE Journals
Semantic Scholar

Table 1 – Databases found through Google Scholar.

All these databases hosted relevant material to the research question, filtered by the criterion in *chapter 4.2* and checklist in *chapter 4.3* through the Google Scholar search hits. Further details regarding the search string are presented in the *chapter 4.1*, "Search string" in the methodology.

The search string previously used in Google Scholar is adapted to IEEE-Xplore using their advanced search tool, additionally separate search string(s) are adapted for each database specifically through rigorous testing of the goal finding the densest result of relevant hits, as mentioned in the methodology *chapter 4.1*.

Presented following is *table 2*, with the dates corresponding to each of the searches on their related databases from the *table 1* list, and the search string used for each specific case that list. Presented are also the number of search hits and the remaining results after the criterion (4.2) and data extraction (4.4).

Date & Database(s)/Archive(s):	Search string(s):	Nr. of hits:	Remaining after criterion (4.2):	Remaining after data extraction (4.4):
IEEE-Xplore 2021-04-13	("Full Text & Metadata":Smart Home) AND ("Full Text & Metadata":IoT) AND ("Full Text & Metadata":Protocol) AND ("Full Text & Metadata":Framework) AND (("Full Text & Metadata":KNX-RF) OR ("Full Text & Metadata":ZigBee) OR ("Full Text & Metadata":Z-Wave) OR ("Full Text & Metadata":Wi-Fi) OR ("Full Text & Metadata":Bluetooth) OR ("Full Text & Metadata":EnOcean) OR ("Full Text & Metadata":Thread))	4447	99	28
IEEE-Xplore 2021-04-18	("Full Text Only":Smart Home) AND ("Full Text Only":Gateway) AND ("Full Text Only":Interoperability)	4504	90	6
MDPI 2021-04-15	(@(full_text)smart%20home@(full_text)gateway@(full_text)interoperability)	165	2	0
TUE 2021-04-15	"Multi-protocol" AND "IoT"	3	1	0
TUE 2021-04-15	"Smart home" AND "Interoperability"	53	4	0
Aalto University 2021-04-15	"Smart home" AND "Interoperability"	74	2	0
Chalmers 2021-04-15	"Smart home" AND "Interoperability"	18	3	1
University of Stuttgart 2021-04-15	Smart home gateway	76	1	0
JEJU National University 2021-04-15	Smart home interoperability	14	3	1
DiVA 2021-04-15	“Smart home” AND “Interoperability”	10	3	0
Korea Science 2021-04-15	Smart home and interoperability	13	3	0

Re-searchGate 2021-04-15	"Smart home" AND "Interoperability"	100	15	3
Core 2021-04-15	"Smart home" AND "Interoperability"	656	23	1
Sage Journals 2021-04-15	“Smart home” AND “Interoperability”	36	8	2
Semantic Scholar 2021-04-16	"Smart home" AND "Gateway" AND "Interoperability" AND "IoT"	573	55	9

Table 2. Search string hit results and filtration through methodology.

6 Analysis and results

Here is the comprehensive result compiled from the extracted data during the process of methodology, described previously in chapter five, mapping different solutions of accomplishing interoperability within the smart home network communication into tables and categories (Braun & Clarke, 2006).

Every result after completed analysis is documented in the paper through a table in the following sub-chapters, explaining the different categories of each mapped material.

6.1 Categorizing the material

Categorization in the form of mapping each of the found used communicative protocols, frameworks and architectures in their respective category responding to the reference of the related material from the gathered material. Each new mapped solution is provided with a short explanation and brief overview in the Central Concept sub-chapter (2.3), under the background chapter.

Whereas some scientific articles mix both a literature review surrounding an area and follow up with an experimental effort or a case review surrounding their findings (Desai, Sheth and Anantharam, 2015), they may have conclusions or findings in more than a single solution, consequently they may then be mapped in more than one category as the material has answers to more.

Moreover, frameworks often cover a broad spectrum and consequently uses several protocols to accomplish this. This in turn also result in that a framework may be mapped into several categories as its case span over a broader spectrum than interoperability at a single layer in the OSI model, a capsule solution that embark to cover both technological interoperability between the networking communicative protocols as well as semantic data transparency at the higher spectrum (Farooq, Wheelock and Pesch, 2020). This often result in a solution which forwards data to an online cloud-based application through an internet-gateway, instead of translating the application data locally (Kim et al. 2014). An interoperable solution towards achieving technical networking capabilities but lacks other interoperable capabilities that cover the rest of the spectrum from physical to application interoperability, an example would be a networking protocol converter at the central gateway of the house which opens communication possibilities but does not translate the semantic data within for the application layers (Rahman and Chakraborty, 2018), or as a protocol conversion (Narayanan and Murthy, 2021). This often result in a local-based solution as an edge-gateway in the house, integrating communications and forwards it. Consequently, this achieves network protocol interoperability or implement solutions towards accomplishing it, although it may not be a fully adaptable solution for a fully interoperable smart home through-out the whole spectrum, as such it does not often map itself into several categories as the use case presented is limited to a narrower spectrum, consequently fewer layers.

6.2 Part 1 - Protocols & frameworks discovered in the material.

The process of analysis will stem in finding the protocol and frameworks in which the result material source utilized in their approach to achieve an interoperable solution. To draw patterns in which protocols and frameworks are commonly used in adapting wireless interoperability within the smart home.

Categorizing these results will provide a good overview on how interoperability is accomplished throughout the whole spectrum of communication as well as giving insight in which protocol or framework is more adaptable than others from this use case. Although it would merely be an insight and loosely based.

Whenever a new protocol or framework is found from the material source it will be documented in the central concept chapter with a brief explanation. This will provide a basic understanding of each solution towards accomplishing interoperability within the smart home.

The technical protocols used within the material source are also mapped and documented, as it does provide an overview on which technical transmission protocol is more interoperable when adapting frameworks and interoperable protocols, even though the technical transmission protocol itself may stem from heterogenous characteristics, it still provides an insight into which technical communications are used to adapt interoperability as well as increase transparency and objectivity by gathering every communicative protocol and framework regardless of how interoperable it is, to then later analysis their respective characteristics in the following chapter 6.3 (Braun & Clarke, 2006).

Architecture/Framework	**Protocol**	**Material source(s)**
	CoAP	(Samuel, 2016), (Florea, Rughinis, RusE, Dragomir, 2017), (Sinche et al, 2020), (Al-Masri, et al. 2020), (Taj, Asad, Azhar and Kausar, 2019), (Masek et al, 2016), (Aly, Khomh, Guéhéneuc, Washizaki, Yacout, 2019), (Abdelouahid, Oqaidi and Marzak, 2018), (Kang, Kim and Choo, 2017), (Morabito, Petrolo, Loscrí and Mitton, 2016), (Farooq, Wheelock and Pesch, 2020), (Žitnik, Janković, Petrovčič and Bajec, 2016), (Lei Hang, 2017), (Desai, Sheth and Anantharam, 2015)
REST		(Taj, Asad, Azhar and Kausar, 2019), (Bronsted, Madsen, Skou and Torbensen, 2010), (Kim et al. 2014), (Huang and Tseng, 2016), (Parocha and Macabebe, 2019), (Keinestam, 2016), (Uviase and Kotonya, 2018), (Chattopadhyay, Samantaray and Datta, 2018), (Desai, Sheth and Anantharam, 2015)
	SIP	(Hosek et al, 2017), (Masek et al, 2016), (Zhang, Ji, Liu and Song, 2018)
	XMPP	(Al-Masri, et al. 2020), (Masek et al, 2016)
ALLJoyn (OCF)		(Sinche et al, 2020), (Singh, Dwarakanath, Haribabu and Babu, 2017), (Vivek, Verma and Krishnan, 2018), (Konduru and Bharamagoudra, 2017), (Gambi, Montanini, Raffaeli, Spinsante and Lambrinos, 2016), (Kang, Kim and Choo, 2017), (Santofimia et al, 2018)
	MQTT	(Florea, Rughinis, RusE, Dragomir, 2017), (Al-Masri, et al. 2020), (Masek et al, 2016), (Aly, Khomh, Guéhéneuc, Washizaki, Yacout, 2019), (Abdelouahid, Oqaidi and Marzak, 2018), (Morabito, Petrolo, Loscrí and Mitton, 2016), (Khanchuea and Siripokarpirom, 2019), (Parocha and Macabebe, 2019), (Ozeer, Letondeur, Ottogalli, Salaün and Vincent, 2019), (An, Hwang and Song, 2016), (Žitnik, Janković, Petrovčič and Bajec, 2016), (Liu, Akram Hassan,

		Karlsson, Pang and Gong, 2019), (Ray, Thapa and Dash, 2019), (Ramírez, Taha, Lloret and Tomás, 2020), (Tamri and Rakrak, 2021), (Uviase and Kotonya, 2018), (Li, Nie, Chen, Zhan, and Xu, 2015), (Chattopadhyay, Samantaray and Datta, 2018), (Budakoti Gaur and Lung, 2018), (Kim, Choi, and Rhee, 2015), (Desai, Sheth and Anantharam, 2015)
DDS		(Al-Masri, et al. 2020), (Masek et al, 2016), (Abdelouahid, Oqaidi and Marzak, 2018)
	AMQP	(Al-Masri, et al. 2020), (Masek et al, 2016), (Abdelouahid, Oqaidi and Marzak, 2018), (Uviase and Kotonya, 2018), (Chattopadhyay, Samantaray and Datta, 2018), (Budakoti Gaur and Lung, 2018)
	Z-Wave	(Taj, Asad, Azhar and Kausar, 2019), (Aly, Khomh, Guéhéneuc, Washizaki, Yacout, 2019), (Bronsted, Madsen, Skou and Torbensen, 2010), (Kim et al. 2014), (Farooq, Wheelock and Pesch, 2020), (An, Hwang and Song, 2016), (Žitnik, Janković, Petrovčič and Bajec, 2016), (Sowah et al, 2018), (Li, Fang, Wang and Daneshmand, 2019)
	ZigBee	(Taj, Asad, Azhar and Kausar, 2019), (Aly, Khomh, Guéhéneuc, Washizaki, Yacout, 2019), (Chen, Yin and He, 2020), (Narayanan and Murthy, 2021), (Rahman and Chakraborty, 2018), (Uddin, Mukherjee, Chang and Lakshman, 2018), (Amiruddin, Ratna, Harwahyu and Sari, 2018), (Aloi et al, 2016), (Khanchuea and Siripokarpirom, 2019), (Yang, 2017), (Götz and Kanoun, 2018), (Ding, Song, Tong and Li, 2016), (Bronsted, Madsen, Skou and Torbensen, 2010), (Kim et al. 2014), (Farooq, Wheelock and Pesch, 2020), (Huang and Tseng, 2016), (Žitnik, Janković, Petrovčič and Bajec, 2016), (Zhang, Ji, Liu and Song, 2018), (Khajenasiri, Zhu, Verhelst and Gielen, 2015), (Kim, Boulos, Yackovich, Barth, Beckel and Mosse, 2012)
	Wi-Fi	(Aly, Khomh, Guéhéneuc, Washizaki, Yacout, 2019), (Chen, Yin and He, 2020), (Narayanan and Murthy, 2021), (Amiruddin, Ratna, Harwahyu and Sari, 2018), (Aloi et al, 2016), (Khanchuea and Siripokarpirom, 2019), (Ding, Song, Tong and Li, 2016), (Kim et al. 2014), (Farooq, Wheelock and Pesch, 2020), (Huang and Tseng, 2016), (Liu, Akram Hassan, Karlsson, Pang and Gong, 2019), (Zhang, Ji, Liu and Song, 2018), (Ray, Thapa and Dash, 2019), (Li, Fang, Wang and Daneshmand, 2019), (Santofimia et al, 2018), (Florea, Rughinis, RusE, Dragomir, 2017)
	Thread	(Singh, Dwarakanath, Haribabu and Babu, 2017), (Vivek, Verma and Krishnan, 2018), (Farooq, Wheelock and Pesch, 2020), (Liu, Akram Hassan, Karlsson, Pang and Gong, 2019)
	EnOcean	(Khajenasiri, Zhu, Verhelst and Gielen, 2015)
	Bluetooth & BLE	(Chen, Yin and He, 2020), (Narayanan and Murthy, 2021), (Rahman and Chakraborty, 2018), (Uddin, Mukherjee, Chang and Lakshman, 2018), (Aloi et al, 2016), (Ding, Song, Tong and Li, 2016), (Farooq, Wheelock and Pesch, 2020), (Žitnik, Janković, Petrovčič and Bajec, 2016), (Ray, Thapa and Dash, 2019), (Li, Fang, Wang and Daneshmand, 2019), (Santofimia et al, 2018)
	LoRa (LoRaWAN)	(Florea, Rughinis, RusE, Dragomir, 2017), (Aly, Khomh, Guéhéneuc, Washizaki, Yacout, 2019), (Amiruddin, Ratna, Harwahyu and Sari, 2018), (Liu, Akram Hassan, Karlsson, Pang and Gong, 2019)
	6lowpan	(Florea, Rughinis, RusE, Dragomir, 2017), (Aly, Khomh, Guéhéneuc, Washizaki, Yacout, 2019), (Farooq, Wheelock and Pesch, 2020)
OneM2M		(Singh, Dwarakanath, Haribabu and Babu, 2017), (Vivek, Verma and Krishnan, 2018), (Taj, Asad, Azhar and Kausar, 2019), (Aly,

		Khomh, Guéhéneuc, Washizaki, Yacout, 2019), (Yang, 2017), (An, Hwang and Song, 2016), (Žitnik, Janković, Petrovčič and Bajec, 2016)
IoTivity (OCF)		(Konduru and Bharamagoudra, 2017), (Taj, Asad, Azhar and Kausar, 2019), (Farooq, Wheelock and Pesch, 2020), (Li, Fang, Wang and Daneshmand, 2019), (Lei Hang, 2017)
Google Weave		(Konduru and Bharamagoudra, 2017)
Apple HomeKit		(Konduru and Bharamagoudra, 2017)
UPnP (OCF)		(Taj, Asad, Azhar and Kausar, 2019), (Hosek et al, 2017), (Kim, Boulos, Yackovich, Barth, Beckel and Mosse, 2012)
OpenHAB		(Parocha and Macabebe, 2019)
	SOAP	(Taj, Asad, Azhar and Kausar, 2019), (Zhang, Ji, Liu and Song, 2018)
OSGi		(Taj, Asad, Azhar and Kausar, 2019), (Hosek et al, 2017), (Kato, Matsubara, Yoshida and Ishikawa, 2016), (Kim, Boulos, Yackovich, Barth, Beckel and Mosse, 2012)
	IR	(Huang and Tseng, 2016)
PUCC		(Kato, Matsubara, Yoshida and Ishikawa, 2016)
	UWB	(Khajenasiri, Zhu, Verhelst and Gielen, 2015)
ESH		(Smirek, Zimmermann and Beigl, 2016)
URC		(Smirek, Zimmermann and Beigl, 2016)
	Insteon	(Kim, Boulos, Yackovich, Barth, Beckel and Mosse, 2012)
SDN		(Uddin, Mukherjee, Chang and Lakshman, 2018), (Tamri and Rakrak, 2021), (Budakoti Gaur and Lung, 2018)

Table 3 – Categorizing protocols and frameworks from the material.

6.3 Part 2 - Categorizing the discovered solutions in relation to the research question.

Here the discovered protocols and frameworks from the previous table, are mapped into different levels of interoperability, communicative spectrum, and adaptability to the smart home environment. To give an assessment in how they operate towards in conjunction to interoperability within smart homes. The mapping will also provide useful insight in how each interoperable issue is tackled through-out each communicative layer as well as an assessment from corresponding research article on how adaptable the solutions are.

In correspondence to the research question, the wireless capabilities of each protocol and framework will also be mapped and categorized to provide analysis of relevance to medium adaptation in terms of wireless communication.

The OSI model layers will be cut-out to three raw estimates, as a discovered limitation of IoT communication is their different way of handling the communication stack and as such does not directly translate to the seven layered OSI model or TCP/IP model. However, it will still provide a good estimate on where each protocol or framework operates regarding communication but mapping the solutions one-to-one corresponding to specific layers in the OSI model is not feasible for every protocol as IoT does not always follow the traditional model (Mehta and Sahai, 2017).

The mappings are based upon information provided by the result material in *table 3* and previous background research related to this current study, and as previously mentioned in validity chapter, the material amount is vast, and the process categorization is of extraordinary complex process and always include a risk of subjectivity.

Letters marked with asterisk in *table 4, 5 & 6* may be applicable to more than one scenario, such as the Apple HomeKit can achieve full interoperability within an Apple-based environment, but not with other proprietary devices (Konduru and Bharamagoudra, 2017). Whereas SDN is a definition of architectural software networking, it can be interpreted openly in the application layer depending on the specific implementation scenario (Software-Defined Networking (SDN) Definition - Open Networking Foundation, 2021). Same goes for Thread as it has open possibilities for several interoperable solutions within the application layers (Singh et al., 2017). Consequently, these markings should be taken with extra consideration as they slightly fall out of the spectrum of categorization within the tables.

Moreover, the tables will also be filled by several predefined values to different categories depending on the interoperable, communicative, wireless, and adaptable characteristics each protocol or framework withhold, correlating to the name of protocol or framework and the applicable estimates, each value and category is defined in the following sub chapters.

6.3.1 Categorizing the level of interoperable capabilities

This categorization is to map in which interoperable capabilities the solution has, whether it is a protocol, framework, or architecture. As every communicative solution used or discovered towards interoperability in the material from 6.2 is gathered for analysis, some solution may be more interoperable than others and as such needs analysis for conclusive results.

None, abbreviation N– This value corresponds to something heterogenous, the letter is defined to categorize protocols or frameworks which are completely heterogenous to their proprietary nature. Such as a technical protocol which has no additional specification towards interoperability characteristics within the datasheet, as such it inherently lacks capabilities to communicate with other technologies outside of its own spectrum of adaptation, an example would be most of the IEEE communication standards within Wi-Fi, as they define technological standards with specifications towards communication within a specific spectrum but lacks adaptation towards integration of other outside technologies (Chen, Yin and He, 2020). Consequently, this mapping does not provide any interoperability in on itself.

Low, abbreviation L – This value corresponds to lower interoperable functionality, an example would be what Kotstein and Decker (2019) define as technical interoperability, which in accordance to their study is defined as to if both components are physically connected to each other and can transmit any kind of information up to the transmission layer, this however does not enable a fully interoperable line of communication all the way towards the end-user but merely enables local device-to-device functionality, the context of the message interpretation is excluded. The level of interoperability in this lower spectrum addresses to the lower communicative layers of the OSI model, the physical, data link, network, and transport layer. Rahman and Hussain (2020) describe technical interoperability as the ability to communicate among various devices using different protocols, technologies, software, and operating systems.

Medium, abbreviation M – a middle ground which adapts interoperability in the higher semantic layers but not through-out the whole spectrum of communicative layers, an example would be what is commonly referred to as middleware, AMQP for example. AMQP which is based upon the higher spectrum of communication at the application layer, AMQP adapts heterogenous platforms and devices though its application-based message-oriented iddleware which through a common language can interoperate machine-to-machine communication including messaging, routing, and security in a post-facto measure (Al-Masri, et al. 2020). Being a semantic middleware as AMQP however does not by default adapt the whole smart home into a full interoperable centralized home as it solely defines a common language at the application layers, as such it can interoperate the communication before the end-user, but it is however not a tool towards achieving direct technical interoperability in the lower layers of communication. Middleware's may often be included in a framework or architecture which does define a fully adaptable interoperate solution for a disjoint smart home (Budakoti Gaur and Lung, 2018).

High, abbreviation H – Highly interoperable, this value maps itself as a definition of a solution which provides efforts towards a full capsule solution for the whole smart home, adapting an interoperable communication throughout multiple layers communication, from technical to the end-user's application interaction, an example would be an architecture such as OpenHAB, used to integrate different technologies and devices within the home, with automation functionality and centralized monitorization and control, an adaptable architecture to adapt full interoperability within the home (Parocha and Macabebe, 2019). This type of higher interoperability solution often revolves around several complied protocols or even frameworks, towards interoperability and through compiling them can apply interoperability through-out the stack of communication, in a more accessible way to the end-user. Providing the consumer with a more flexible way of integrating the home (Parocha and Macabebe, 2019).

6.3.2 Categorizing the communicative spectrum

This categorization is to pinpoint in which communicative spectrum the interoperable solution is applied at, whether it is a protocol, framework, or architecture towards interoperability. As some solutions from the material may only perform interoperable characteristics in certain parts of the communication. To have an easier understanding of their implementation in the spectrum of communication, the OSI Layer will give a rough estimate on each communicative framework or protocol in which spectrum they adapt. For a brief overview of the OSI layers, see the sub-chapter 2.3.1 under Central Concepts (ISO/IEC 7498-1:1994, 1994).

Lower layer (Technical), abbreviation L - Within this current study, the technical lower layer of communication will be defined as the physical- and data-link layer corresponding to the OSI model, which is layer 1 & 2. This categorization consisting of a lower spectrum estimate in which physical and technical communication is performed, examples would consist of what is presented in the technical data and specifications sheet, including things as radio frequency, theoretical data rate and modulation technique. Direct interoperability at these lowest layers is hard to accomplish in a non-standardized market, unless the protocol, framework or architecture defines dynamical device properties, taking several communication possibilities into consideration (Konduru and Bharamagoudra, 2017). At this kind of communication layer, the interoperability is often focused on different vendor's devices, communication technologies, and protocols for seamless communication, compared to the higher layers of communication which are more message and context based (Rahman and Hussain, 2020).

Middle layer (Networking), abbreviation M - The middle layer of communication in this current study will be defined as the corresponding to the transport- and networking layer in the OSI model, which is layer 3 & 4. Within this spectrum of communication, the routing of the frames towards their specific destination and the reliability within its transmission is covered (Konduru and Bharamagoudra, 2017). The networking layer corresponds to framing data before transmission, from source to destination in variable lengths whereas the transport layer corresponds to reliability of the data transportation, including services such as flow control, congestion avoidance. In relation to this study the networking middle layer can be viewed as a definition of an in-between relating from the lower layered physical- and technical categorization and higher layered application-based semantics and syntax, an example to consider; The commonly known IPv4 and IPv6 corresponds to the networking layer (ISO/IEC 7498-1:1994, 1994).

Higher layer (Syntactic & Semantic), abbreviation H - The remaining higher layer of communication estimates its relation to the fifth, sixth and seventh OSI layer, Session-, Presentation- and the Application layer. This spectrum consists of the last three steps of communication before presenting it to the end-user. Syntax formatting and semantic understanding of data as well as sequence and flow of events handled by the session layer, also as IoT does not relate directly to the well-established OSI model the categorization remains an estimation of communication. Example of communication at this spectrum is the syntax and semantics of data, corresponding to the function of applications and software and how data is interpreted and implemented. The application layer can be seen as an abstract from the rest of the protocol stack, highly adaptable with shared communication and includes messaging protocols such as CoAP and AMQP in its spectrum, what makes this mapping considerably more difficult within IoT is that the some communication which is usually labeled as lower layered is post-facto applied in the higher layers through message protocols as the two previously mentioned (Al-Masri, et al. 2020; ISO/IEC 7498-1:1994, 1994). In this current study the message-based protocols such as CoAP and AMQP, even if post-facto applying middle-layered networking will be labeled as a semantic high layered communication.

6.3.3 Categorizing the adaptability correlating to smart homes

This categorization is set to discover how adaptable the solution is in accordance with the research question, in which the solution must be smart home specific within its interoperable characteristics. Accomplished by much like previous categorizations defining predefined values, none, low, medium, and high adaptability towards smart home environments.

None, abbreviation N – The following value corresponds to no relation to smart homes adaptation within communication, as a consequence the value mapping completely lacks use-case and adaptation of installation within a smart home environment, for example a framework specifically designed and tailored for smart city infrastructure interoperability but lacks any direct relation to the environment within the actual home and as such does not relate to the end-user or consumer within the home (Jaloudi, 2015).

Low, abbreviation L – A value mapped within here is applicable to smart homes but not specifically designed for it, such as the application based uniform message protocols as CoAP and AMQP mentioned earlier. These type of messaging protocols can interoperate most any of technological communication and as such is applicable to much more than just smart homes and does not always provide user friendly installation and adaptation within the home, even if the solution may be very interoperable, as such the use-case may still be inapplicable for most consumers. To take into consideration is that some architectures or frameworks may adapt these message protocols in their solution towards interoperability, but then also provide a more straight-forward turnkey user experience towards home adaptation (Sinche et al, 2020).

High, abbreviation H – This value corresponds to something universally applicable to smart home adaption, a tailored solution for applying interoperable communication within the smart home, such as Google Weave & Apple HomeKit (Konduru and Bharamagoudra, 2017). This mapping is consequently accessible for smart home adaptation for most end-users and consumers in comparison to something that needs to be redefined before adaptation as the previously discussed value Low.

6.3.4 Categorizing the wireless adaptability

The wireless categorization is set to discover and define how adaptable the solution is in accordance with the research question of specifically wireless communication. This mapping will remain quite binary compared to the previous, as either the interoperable solution is wirelessly applicable, or it is not. Consequently, it will only have two values for mapping.

Yes, abbreviation Y – This value maps itself as wirelessly communicatively applicable towards the interoperable smart home (Lan et al., 2019). To take into consideration are solutions in the higher layers of communication, as the technical transportation is completely insignificant for these types of interoperable solutions and therefore are automatically wirelessly applicable.

No, abbreviation N – This value maps itself as not remotely being wirelessly applicable to communication, such as a solution which revolves around introducing interoperable characteristics though cabling and therefore does not adapt interoperability within wireless communication (Kim et al., 2012).

Following are the protocols presented in a table of analysis with corresponding mapping, using the predefined categorizations discussed in the previous sub-chapters.

Protocols	Interoperability (6.3.1)	Communication Spectrum (6.3.2)	Smart home adaptability (6.3.3)	Wireless adaptability (6.3.4)
CoAP	M	H	L	Y
SIP	M	H	L	Y

XMPP	M	H	L	Y
MQTT	M	H	L	Y
AMQP	M	H	L	Y
Z-Wave	M*	L, M, H	H	Y
ZigBee	N	L, M, H	H	Y
Wi-Fi	N	L	L	Y
Thread	H	L, M, H*	H	Y
EnOcean	M*	L, M, H	H	Y
Blue-tooth	N	L, M	L	Y
Lo-RaWAN	N	L	N	Y
6lowPAN	M	M	L	Y
SOAP	M	H	L	Y
IR	N	L	N*	Y
UWB	N	L	N*	Y
Insteaon	L	L	H	N*

Table 4 – Categorizing interoperability within the discovered protocols.

Much like the previous table, the following *table 5* will also discover corresponding mappings through analysis of the frameworks and architectures, using the predefined categorizations discussed in the previous sub-chapters.

Frame-works & Archi-tectures	**Interoperability (6.3.1)**	**Communication Spectrum (6.3.2)**	**Smart home adaptability (6.3.3)**	**Wireless adapta-bility (6.3.4)**
REST	M	H	L	Y
UPnP	M	H	L	Y
ALLJoyn	M	H	L	Y
DDS	M	H	L	Y
OneM2M	M	H	L	Y
IoTivity	H	H	L	Y

Google Weave	H	H	H	Y
Apple HomeKit	H*	H	H	Y
Open-HAB	H	H	H	Y
OSGi	M	H	L	Y
PUCC	M	H	L	Y
ESH	H	H	H	Y
URC	M	H	L	Y
SDN*	M	H	L	Y

Table 5 – Categorizing interoperability within the discovered frameworks & architectures.

To assess which protocol, framework or architecture withhold high relevance to the research question, an analysis of technologies with high adaptation, high interoperable characteristics and wireless capabilities will be presented. With the help of table 4 and 5 gathering every solution with a value of "**H**" in both Interoperability (6.3.1) and Smart Home Adaptability (6.3.3), with the solution also withholding a wireless capability, consequently the category Wireless Adaptability in *table 4 and 5* must be marked with "**Y**". This will give an overview of the most adaptable and interoperable solutions discovered within the result material, to smart homes specifically, which withhold the requirements of the research question of wireless interoperable offerings to smart homes.

Following is then table 6 presented, with an overview of the most adaptable discoveries in accordance with the research question, utilizing the analysis through-out *table 4 & 5*. Requirements are high interoperability, smart home adaptability and wireless adaptability in relation to the *table 4 & 5* mappings.

Findings with high correlation to the research question requirements
Thread
Apple HomeKit*
Weave
OpenHAB
ESH

Table 6 – Solutions with high correlation to the RQ.

7 Discussion

To begin discussions, assess the findings from chapter six with their correlation to the research question of; "Which options towards wireless communication interoperability are available for smart homes?", will be discussed.

In the research question, the current study described to evaluate different smart home communicative protocols and their solution for tackling interoperability as well as possible frameworks and architectures capable of achieving interoperability within a heterogeneous environment.

The terminating findings presented in *table 6* gives an assessment of which solution held the most correspondence to the research question, as smart home adaptation is of high availability correlating to the categorization described in chapter 6.3.3, interoperability is of high availability as described in the categorization of interoperability in chapter 6.3.1 as well as the wireless applicability of the solution is a possibility as the categorization in chapter 6.3.4 describes.

From the ultimate findings only one protocol withheld the mapping requirements to the research question, namely Thread. Although several frameworks were also present as they possessed four out of five spots in the concluding *table 6*, namely Apple HomeKit, Google Weave, OpenHAB and ESH. As mentioned during the analysis, Apple HomeKit should be taken into extra consideration as it inherently falls short of the other mapping in terms of being proprietary vendor-locked, although made all the requirements of mappings and open for accessible smart home interoperability within an environment based on that vendor.

Deviations from the research goal is the lack of findings towards interoperable solution specifically tailored at the technical plane of interoperability, meaning at the lower levels of communication, defined as communication spectrum L in *table 4 & 5*. The results show heavy inclination towards interoperable solutions in the higher spectrum of communication when viewing the mappings of *table 4 & 5*, which however goes in conjunction with the background research of achieving post-facto interoperability within real-time communication.

What is also remarkable regarding the findings of *table 4 & 5*, is the heavy redlining towards capabilities of interoperability at the higher layered software-based communication, defined as Software Defined Networking (SDN). Observed in *table 4 & 5* as solutions mapped as communicative high layered solutions, which also providing medium to high interoperability characteristics with inherent wireless adaptability as the technological transport medium hold insignificance in their functionality, being application-based solutions. All the ultimate findings presented in *table 6* in correlation to the research question had one foot or more dipped in SDN within their solution for communication and interoperability. What is also interesting is the initial background research held no hint towards this, thus making these findings deviating the current study somewhat, in correlation to the initial expected results. Consequently, most of the interoperability discovered within the material and analysis process is heavily sided towards SDN.

If drawing the conclusion that an end-user within the field wants a turn-key solution for the home, a completely adaptable solution covering all spectrum of interoperability throughout the smart home is desired compared to only applying an in-between solution, as the spectrum of communication through a protocol stack needs to be interoperable though-out from the physical medium to the end-user's application, consequently the *table 6* mappings correlate well to these requirements. However, if developing an own tailored solution, the mapping towards interoperability and having the communicative spectrum as correlation in *table 4 & 5* will provide developers and researchers with a better overview of available solutions towards an interoperable smart home.

An interesting note is that some technical protocols within *table 4* also hold optional capabilities all the way to the application layer, some even with optional interoperate capabilities at the higher layers such as Z-Wave and EnOcean, by utilizing SDN. Another interesting note is the most recurrent solution in the result material, the ALLJoyn framework, although it did not map itself closest to the research question and whereas this current study is not a statistical quantitative study, an interesting note to consider is still the recurrent use of this interoperate solutions within the material as it was used in over seven different studies towards interoperability.

Eclipse Smart Home (ESH) was during the end of the current study, been marked as "archived" by the eclipse foundation but will remain in the findings as it was of relevance for most of the study and may still be assessable soon again.

Noteworthy to take into consideration as mentioned before, is the Apple HomeKit, as it can achieve full interoperability only within an Apple-based environment, but not with other proprietary devices, consequently it was marked with an asterisk in *table 5*, as Apple decided to adapt interoperability within vendor-lock. Another notable consideration is that SDN is a definition of an architectural approach and not a fully-fledged ready-to-go solution in on itself, consequently it is marked with asterisk in *table 5* just as Apple HomeKit, for their respective deviations.

7.1 Future work

The strive towards interoperability is a constant process and many initiatives work towards standardized solutions, as this study have aimed to shed light on the fragmented market and the interoperable solution for heterogenous network communication within the smart home.

The next logical step in development is to evolve efforts towards a standardized market, which can bring interoperability by default and not as a post-facto framework. While there already are several initiatives and consortiums towards standardization, the smart home market is still very fragmented, with the end-user easily being interlocked in a single proprietary solution without dynamical adaptation in the wider range of devices.

Therefore, a need for development in this area of standardization is sought-after and highly anticipated. Although scattered efforts can bring fragmentation in and of itself and joint development is desirable.

Another suggestion unrelated to the first; Is to compare performance between a single heterogenous wireless protocol such as Z-Wave to a multilayered framework solution, which is based around software defined networking. As degradation in performance is quite possible when translating technical communication, to later perform the networking at a software level, as SDN. This however may also present open unwanted holes for possible degradation regarding security surrounding the smart home.

Having in mind the uncovered findings of different interoperable protocols and frameworks with different characteristics regarding communicative spectrum and interoperable capabilities in the analysis section, a purposed research area is experimental studies to define objective takes on how the different findings can be adapted in different environments may be of use for both consumer sector and researchers assessing different smart home environments.

7.2 Limitations

Here are limitations presented, hurdles, struggles and obstacles in which this research accumulated through-out the process of completion.

OSI layer estimation mentioned in this paper should be taken with slight precaution, as IoT has a wide variety of unique devices and communicative solutions which utilize different methods for transmission compared to traditional TCP/IP networks, as well as many of the discussed interoperable solution utilize software defined networking (SDN), which simulate networking on the higher layers of the OSI model to interoperate technical heterogenous devices into a common language at the higher plane. Whereas also some of the discussed solutions are architectural frameworks lending technologies from several different protocols to accomplish their goal. Consequently, making a clear one-to-one OSI layer mapping is far more complex than initially planned and as such it was for the most part neglected.

As the methodology solely revolves around literature, it does lack any hands-on experience from field practice and experiments in the area. Moreover so, the study cannot bring any new revelations around smart home interoperability, but rather lift an extensive amount of previous research for future work and development on a grander scale.

Whereas this study is also done as a bachelor thesis spanning through the spring term of 2021, it does have a set time frame until completion, which also limits the amount of time at hand.

Another barrier is the knowledgeable language of this study, this could through the inclusion criteria "*Articles written in either English or Swedish*" neglect any articles written in other languages and as such has potential to deviate the results. Another similar deviation is the exclusion criteria" *The article is not locked by payment, outside of what is offered by the University of Skövde*", as there is a potential of valuable information being neglected here.

The research mainly focused on the protocols found during the background and related work assessment, as such the predefined search strings are limited to those and by that reason, search results may neglect other protocols which were not mentioned or documented in the examined articles during the initial steps of this research. However, any communicative protocol found during the process was added along the way into consideration.

A comprehensive limitation was the search result limitation of Google Scholar, with a hard cap of the capabilities of displaying more than thousand results. Which in a well published field as IoT gave this research clear limitations as a systematic literature review aims to identify every relevant material on the subject (Kitchenham, 2004), due to this limitation the methodology had to be revised to discover which databases held material relevant to the research question in hand, instead of just relying heavily on Google Scholars search result. Although the current revised methodology still uses Google Scholar to uncover relevant databases surrounding the research field.

As the findings from the analysis is comprehensive and covers several protocols and frameworks, the current study does neglect any detailed explanation on how the specific solutions can be adapted. Reason being the lack of hands-on experience within the different solutions as well as each discussed protocol or framework is very comprehensive in on of itself and would require an experimental methodology to objectively assess an optimal adaptation of different home environments.

7.3 Ethical questions

The interoperability within smart home communications in on itself does not raise many ethical questions, but smart homes in general certainly does. As this study aims to provide questions regarding automation and standardization of smart home it indirectly relates to the ethicality of smart home adaptation as a whole and their devices. In this chapter the issues surrounding the ethicalities of smart home adaptation will be discussed.

A well-adapted smart home will provide the end-user with great monitor and control over responding devices within the home, some examples are home environmental control, security, and entertainment. These are all positive characteristics, but it also opens up the same control of the end-users' home to an ill intent hacker, if any security would be compromised or breached when applying these interoperable and post-facto framework solutions to the home, giving the aggressor even more power within the compromised home.

Inherently, the market has become fragmented from some manufacturers goal to interlock the consumer to their infrastructure for financial benefits. As such these interoperable imitative have become a big movement in the past years, whereas they do not intent to cause ill side effects such as compromised security, it can become a reality when developing new communicative solutions.

In adopting post-facto solutions, a risk of degradation of original communicative performance is possible, which can be catastrophically in terms of health monitoring or medical devices within the home, as well as many other high-stake installations which may be responsible for life dependent tasks.

8 Conclusion

Concluding the results and discussions, this study presents results related to wireless smart home interoperability and which communicative solutions such as protocols and frameworks, hold capabilities towards accomplishing interoperate home environments. With assessment in relation to where each solution is in correlation to the research question and in the spectrum of communication layers corresponding to an OSI layer estimate, as seen in table 4, 5 and 6. Of solutions which can fully adapt the smart home communication in relation to the discoveries within *table 4 & 5*, presented in *table 6,* goes to the Thread protocol and the Apple HomeKit, Google Weave, OpenHAB and ESH framework, which is able to fully adapt a home into integration of communicative interoperability and withholds wireless capabilities.

The concluded redlining from the *table 4 & 5* mapping, is the heavy siding towards adopting interoperability within the smart home through Software Defined Networking (SDN), as 23 of the 31 discovered technologies within the material withheld some sort of interoperable framework within the application layer of communication. Retrofitting communication from the technical lower layers to be done at the higher software layers, this type of solution is defined as SDN. Advantages with SDN is the ability for device manufacturers and consumer to choose whichever networking technology which fits best for their use case, to then retrofit the network interoperability through the technologies within the application layer of communication through SDN.

This current study would benefit from additional experimental research within each interoperate solution to smart homes presented, to objectively assess their adaptation, use case and performance in different smart home environments corresponding to each discovery, as such this would be a recommended future work assessment, more detailed future work recommendations can be seen in the *subchapter 7.1*.

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