HISTORY OF IOT, AUTOMATION PROTOCOLS AND SMART HOME

ABSTRACT

This article aims to provide a full picture of the Internet of Things (IoT) artefact through reviewing the history of the relevant technologies. The article intended to provide a better understanding of the interplay between IoT, automation protocols and smart home. This article may help to justify which technology to be used or to be avoided as pros and cons of the technologies are revealed throughout the article.

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VYROX
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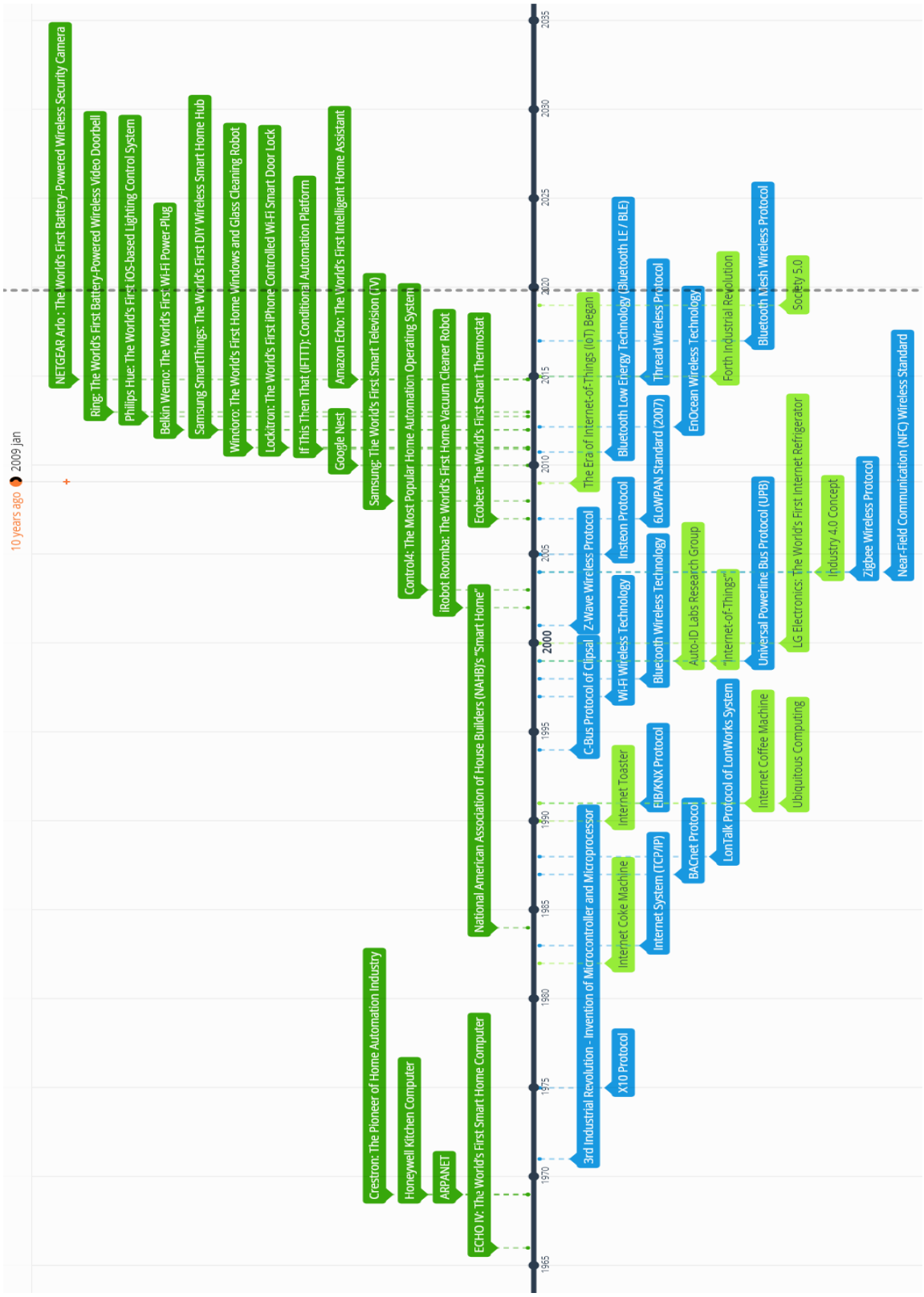
Summary of the History of IoT, automation protocols and smart home systems



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History of Internet-of-Things (IoT)

Internet Coke Machine (1982)

Four computer science graduate students of Carnegie Mellon University (CMU) have realized the concept of Internet of Things (IoT) in the year of 1982 by modified a coke machine with sensors and connected it to the ARPANET, which is the predecessor of the current internet system (Carnegie Mellon University, 1998). This is the first time a physical object was connected to the internet in the human history which anyone can check the availability and temperature status by accessing to the coke machine with command "fingercoke@cmua" from any computer that connected to ARPANET (Carnegie Mellon University, 1998).

Internet Toaster (1990)

An electric Toaster named Sunbeam by Radiant Control company was connected to the internet in the year of 1990 for power and darkness controls with timer using Simple Networking Management Protocol Management Information Base (SNMP MIB) TCP/IP by John Romkey who implemented the first TCP/IP for the International Business Machines (IBM) Corporation PC (Romkey, 2017).

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Internet Coffee Machine (1991)

Following the internet coke machine and internet toaster, University of Cambridge has made the world's first connected coffee machine in the year of 1991 which enabled brewed coffee availability status checking using low-frame-rate video over the internet in order to offer convenience and save the valued time of fifteen researchers especially who lived at other parts of the buildings (Fraser, 1995). Paul Jardetzky has developed a server program to retrieve image and update to client software made by Quentin Stafford-Fraser over the internet every twenty seconds from a camera which fixed on stand and pointed at the coffee machine, and they named this as XCoffee (Fraser, 1995). The first officially record published are wrote by Bob Metcalfe in 1992 (Fraser, 2001).

Ubiquitous Computing (1991)

The term of Ubiquitous Computing was first introduced by Mark Weiser in the year of 1988 and it was defined as small and standalone but inter-connected minicomputers function around people which serving a dedicated purpose (Weiser, 1991). In line with the growth of World Wide Web (WWW), the number of ubiquity things which will be using the internet will increase drastically and become more than the number of people on the planet earth in the near future, hence it is significantly important to study its embeddedness on top of its ubiquitous characteristic (Gershenfeld, 1999).

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"Internet-of-Things" (1999)

The term "Internet-of-Things" was used for the first time in the human history during a presentation for Procter & Gamble (P&G) in the year of 1999 regarding an idea of giving object an identity through radiofrequency and equipping them with sensors, hence every object can be tagged, tracked and managed by computers (Ashton, 2009).

Auto-ID Labs (1999)

Sanjay Sarma, David Brock and Kevin Ashton implemented RFID technology to physical objects by giving them RFID tags for identification in tracking and inventory management over the internet (Madakam & Ramaswamy & Tripathi, 2015).

The Era of Internet-of-Things (IoT) Began (2009)

The era of IoT began at a point somewhere between the year of 2008 and 2009 when connected physical objects are more than the world's population combined which mentioned in a white paper by Cisco Internet Business Solutions Group (IBSG) (Evans, 2011).

Industry 4.0 (2011)

Industry 4.0 (I4) is a concept for the industry which covering lights-out smart factory and IoT-based smart manufacturing with emerging computerization technologies (Kagermann, Lukas, Wahlster, 2011). The term "Industry 4.0" was firstly used at the 2011

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Hannover Fair and then officially presented by the working group at the 2013 Hannover Fair (Legewie, 2014).

Forth Industrial Revolution (2015)

Human technologies are evolving exponentially nowadays instead of linear when compared to old days as a new industrial revolution has just begun and it is disrupting every industry all over again for the fourth time with the new level of information propagating speed which is covering all aspects of life and impact towards our every day's activities (Schwab, 2015). The Forth Industrial Revolution unlocked countless possibilities by connecting billions of people with small-sized but powerful computing technologies in order to provide unprecedented storage capacity, to transport real-time information and to convey the world's knowledge to every single individual in no time (Schwab, 2015). The breakthroughs will be multiplied when combined with the concept of industry 4.0 and the emerging technologies like quantum computing, deep learning artificial intelligence, robotics and IoT (Schwab, 2015).

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History of Home Automation Communication Protocols

3rd Industrial Revolution - Invention of Microcontroller and Microprocessor (1971)

In the early of 1970s, the development of semiconductors devices like transistors and its wide application in the computer chips which also known as Integrated Circuit (IC) have catalyzed the Third Industrial Revolution (Shockley, 1950; Gray, 1984; Fitzsimmons, 1994). The invention of microcontroller by Gary Boone and Michael Cochran in the year of 1971 has revolutionized the entire computing world (Augarten, 1983). Microcontroller and microprocessor applications have facilitated the development of computing technologies, factory automation and internet technologies during the Third Industrial Revolution which began from 1970 (Taalbi, 2018). It drastically optimized the design, compacted the overall size and reduced production costs which also accelerated the diffusion of mass-market consumer devices, personal computers and modern home appliances like washing machines, microwave ovens, and telephones (Cantrell, 1998). Microcontroller also eased the design of embedded systems for automobiles, telephones, appliances, and peripherals for computer systems (Heath, 2003).

X10 Protocol (1975)

After four years of the microcontroller being invented, Pico Electronics of Glenrothes, Scotland has developed X10 in the year of 1975, which is the world's first general-purpose home automation network technology and it has been commercialized in 1978. It primarily uses power line for signaling and controls, and radio frequency (RF) for

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linkage of wireless keypads, remote switches and security sensors like motion detectors (Rye, October 1999). Although, X10 has laid a foundation for modern smart home systems but it also consists of numerous of drawbacks like sluggish, limited scalability, low-bandwidth, signal interference problem and insecure unencrypted data transfers which stimulated the emergence of new players with better networking architecture and solutions. (Barker, Irwin & Shenoy, 2017). Variety of X10 based products was sold by international conglomerates with different brand names like Homeminder by General Electric Company (GE), Central Control System (CCS) by Leviton and Home Director by International Business Machines Corporation (IBM) (Home Toys, 1999).

Internet System (TCP/IP) (1983)

Vint Cerf and Robert Kahn has designed a set of communication protocols namely Transmission Control Protocol (TCP) and the Internet Protocol (IP) in 1974 based on open architecture concept which is like BACnet and KNX (Abbate, 1999). A revolutionary inter-connected network was born when TCP/IP implemented to a packet-switching network named Advanced Research Projects Agency Network (ARPANET) (Leiner & Cerf & Clark & Kahn & Kleinrock & Lynch & Postel & Roberts & Wolff, 2009). The term "Internet" was first invented by both internet pioneers, Vint Cerf and Robert Kahn in their 1974 article about the TCP protocol development, and Cerf is widely known as the father of the Internet (Abbate, (1999). In 1989, World Wide Web (WWW) was born, it is an international information system protocol to define and resolve Uniform Resource Locator (URL), a digital address for the purpose of displaying information using internet browser software by translating data which communicating in the form of Interactive HyperText

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Markup Language (HTML) over Hypertext Transfer Protocol (HTTP) between server and clients (Cohen-Almagor, 2011). The internet has undergone massive expansion during 1990 to 1999, from almost nothing to nearly everywhere in just a little more than a year and the aggressive development through the WWW technologies in peer-to-peer (P2P) for personal computing has extended its innovations to modern e-banking, e-commerce, social media and cyber communications which laid a foundation for the Internet of Things (IoT) (Cohen-Almagor, 2011).

BACnet Protocol (1987)

The arrival of a microprocessor-based direct digital control (DDC) systems during the Third Industrial Revolution which is also known as the First Digital Revolution has induced the born of a non-processor and non-programming dependent open standard concept named BACnet, a data communication protocol for Building Automation and Control Networks which was developed in the year of 1987 by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) in cooperation with ANSI, CEN and the ISO (Newman, 2013). The promise of BACnet of backward compatibility has determined its success in 1995 of being accepted as a nationwide standard by the American first via ANSI/ASHRAE Standard 135-1995 and then later by European Union, Korea, Japan, and Russia (Bushby & Newman, 2002). Aligning with the growth of internet, the prompt response of BACnet in fulfilling the new networking technologies need of its users with Ethernet and BACnet/IP adaptor, has brought their BACnet (135) standard to the international level via ISO 16484-5 standard in 2006 (Newman, 2013). ASHRAE maintains BACnet protocol by continuously improvements and additions to the existing

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standard under the supervision of BACnet committee (SSPC-135) by forming Working Groups (WGs) like "LA-WG: Lighting Applications", "LSS-WG: Life Safety and Security" and "IP-WG: Internet Protocol" in order to raise and address system issues (Newman, 2013). BACnet constantly enhances the interoperability by adapting new protocol like Internet Protocol version 6 (IPv6) (ASHRAE, 2014) and wireless technology of ZigBee (Park, Chon, Park & Hong, 2007). BACnet protocol has been integrated for home automation usage by Schneider Wiser Smart Home in 2014 and House Operating System (HOS) in 2015 (Schneider Electric, 2014; House Operating System, 2015).

LonTalk Protocol of LonWorks System (1988)

There was another party also noticed the need of open Building Control System (BCS) beside the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), they are the competitor of BACnet and the creator of LonWorks System who claimed that their protocol, LonTalk has better field level manageability over BACnet (Webster, 2002). LonWorks (ISO/IEC 14908:2008) is a wide-ranging general term for an multi-vendor open standard system created in the year of 1988 by Echelon Corporation, an American company who specializes in sensing, monitoring and control for electronic devices used in event-triggered control network system and it is now owned by Adesto Technologies (Kim, Hong, Yun & Kim, 2005). LonMark is an association that formed in 1994 by manufacturers and integrators in order to standardize LonWorks technologies by making guidelines for LonTalk protocol, and to ensure interoperability between products with its widely recognized certification program (Tudor SAMUILĂ, Bogdan ORZA, Aurel VLAICU, 2007). Generally, a LonWorks system consists three parts,

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LonTalk (an ANSI/EIA-709.1-A-1999 standard control network protocol specification), Neuron Chip (a dedicated network controller) and variety of network management tools (Ferreira, Osório, Calado, Pedro & Sousa, 2010). According to a breakdown of Neuron Chip sales as of June 2000, LonTalk was very prevalent in building automation as 45% of it sold are used in Building Control System (BCS) (Webster, 2002). Although, LonTalk has been opened in 1996 via EIA-709 and was accepted as a standard via ANSI in October 1999 but it is still very few alternatives found in other platforms and this may due to the rise of Ethernet which dynamically enhancing its real-time performance from its fundamental (Webster, 2002). To cope with this deficiency, LonWorks has developed a gateway named iLON in 2000 to route and bridge LonTalk to TCP-IP Ethernet (Webster, 2002).

EIB/KNX Protocol (1991)

Even though the advancement of Building Control System (BCS) for building automation is growing fast since American's open standard BCS technology like BACnet and LonWorks, there are still a standardization trend in the global wired building automation industry origin from the European countries like Belgium. In order to develop a universal open standard for building automation, 15 well-known manufacturers from the electrical industry formed an association named European Installation Bus Association (EIBA) in the year of 1990 and one year later the first open specification was published, and they named it as EIB Standard (Merz & Hansemann & Hübner, 2018). In 1999, EIBA merged with Swiss-based European Home Systems Association (EHS) and French-based BatiBUS Club International to form Konnex (KNX) Association (Gökbayrak & Kılıvan,

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& Akın & Çelebi & Urhan, 2015). From 2003 onwards, KNX protocol started to be accepted as a standard and for markets like Europe (CENELEC EN 50090, CEN EN 13321-1 and 13321-2), China (GB/T 20965), and US (ANSI/ASHRAE 135). After three years of efforts, EIB/KNX Standard was accepted as an international standard for home automation in 2006 via ISO/IEC 14543-3 (Gökbayrak & Kılıvan & Akın & Çelebi & Urhan, 2015). The comprehensive architecture and functionality design of KNX system which covered all the needs of home automation by supporting diversity of physical transmission mediums like twisted pair (KNX.TP), power line (KNX.PL), radio frequency (KNX.RF), and ethernet (KNXnet/IP) has contributed to the success of KNX who now has more than 70% home automation market share in Europe (Gökbayrak & Kılıvan & Akın & Çelebi, & Urhan, 2015).

Comparison of BACnet, LonWorks and KNX

Around the year of 1990, the emerging of the wired control system technologies like BACnet, LonWorks and KNX have led to the active development of building automation industry. The synergy of opened, standardized and interoperable communication protocols used in home automation have enhanced the level of comfort, security and even energy saving in our every day's life. It is important to understand every system in detail and consider factors of different aspects before making an implementation decision as it will be very costly and time consuming to replace. BACnet, LonWorks and KNX originally are based on powerline wiring and twisted-pair cabling, and recently the systems are extended with wireless feature by radio frequency (RF) or Zigbee and internet feature by IP gateways. Different from BACnet and KNX, LonWorks is non-flexible as it

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required a specific processor named Neuron Chip and dedicated Neuron C programming language in making a product based on their LonTalk protocol (Ferreira, Osório, Calado, Pedro & Sousa, 2010). BACnet and LonWorks are originally designed for big and complex buildings which required very specialized technicians in installations and setup while KNX has many certified technicians who also an electrician, as it is a lower budget system which is more suitable for home use (Ferreira, Osório, Calado, Pedro & Sousa, 2010). Networking capability wise, the better the degree of integration freedom, the better the protocol for large buildings and complex environment (Kell and Colerbrook, 2003). BACnet is defied by six protocols and KNX is not limited by topology, both offer better integration freedom compare to LonWorks which relied only on LonTalk use (Ferreira, Osório, Calado, Pedro & Sousa, 2010).

C-Bus Protocol of Clipsal (1994)

In 1994, Clipsal Integrated System (CIS), a business unit of Clipsal Australia company has developed C-Bus, a proprietary closed network protocol for home and building automation which is based on based on a seven layer OSI model and Controller Area Network (CAN) bus communications system (Clipsal Integrated Systems, 2009). It is Unlike X10, C-Bus uses low voltage networking cables which coverage can up to thousand meters, and a bidirectional wireless network in data transmission for better signal reliability. The combination of both wired and wireless protocols has gained Clipsal a huge success in building automation industry including smart home. C-Bus integrated transmission mediums like powerline wiring, twisted pair cabling, wireless Radio Frequency (RF), Infrared (IR), Ethernet and Wi-Fi. It not only able to control home

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lightings, power outlets, curtain motors and water pumps but also able to be integrated into home security alarm systems, video surveillance and audiovisual home entertainment systems. C-Bus is not perfect, it has disadvantages, it is only suitable for new buildings which viable with fully new low-voltage wiring and cabling. Another disadvantage is the C-Bus wireless radio frequency (RF) system unable to offer full functionality of the system which limited the its usability (Al-Kuwari, Ortega-Sanchez, Sharif & Potdar, 2011). Later, Clipsal Australia was acquired by Schneider Electric in 2000, opened its protocol for interoperability integrations in 2008 and introduced Wiser Home Control (a graphical user interface for C-Bus) in 2010 (Clipsal, 2010). Recently C-Bus lighting control family has been discontinued in the US due to a strategic decision which took effect from March 1, 2015 and at the same time it has been replaced by Clipsal Intelligent Lighting Control System (SILC) (Schneider Electric, 2015).

Universal Powerline Bus Protocol (UPB) (1999)

Universal Powerline Bus (UPB) has been developed by Powerline Control Systems (PCS) of Northridge, California in the year of 1999 in order to improve X10 powerline and intended to become its replacement with lower susceptibility to powerline noise and increased range (Heartfield, Loukas, Budimir, Bezemskij, Fontaine, Filippoupolitis & Roesch, 2018).

Wireless Sensor Network (WSN)

Wireless Sensor Network (WSN) is formed by large number of nodes which distributed densely in a specific environment that is being monitored and to be analyzed

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for a phenomenon of interest (Akyildiz, Su, Sankarasubramaniam & Cayirci, 2002; Abd-El-Barr, Al-Otaibi & Youssef, 2005). WSN senses, records and feedback to end-user in real-time for further data processing and appropriate actions (Ali, Ming, Chakraborty & Iram, 2017). WSN drastically reduces the cost of engineering, wiring, installation and setup (Van der Westhuizen, Hancke & Ramotsoela, 2017). WSN has enhanced smart home concept with automation powered by control algorithm based on real-time variety of remote sensing (Lin, 2012). WSN smart home devices nowadays are Do-It-Yourself (DIY) basis with simple installation and mobile APP quick setup, no technician specialist is required (Piyare & Ro Lee, 2013). The functions like auto-discovery and auto-setup will automatically connect the WSN device to the network after installed within the network coverage and being powered on. WSN can be deployed as self-organizing, self-healing networks. Some WSN devices can work on batteries for months and even years without replacement as they use very low-powered radio equipment (Ehiagwina & Kehinde & Iromini & Sidiq & Punetha, 2018). Under normal circumstances, WSN devices are cheap to manufacture in large numbers as such systems do not need very high network speed and big bandwidth which simple ordinary devices will do (Wang & Balasingham, 2010). The characteristics of WSN devices like low cost, low power and support large number of nodes in a single network have accelerated the development of tomorrow's wireless world (Knight, 2006).

Wi-Fi Wireless Technology (1997)

Wide-Fidelity (Wi-Fi) is a trademark of a wireless technology under IEEE 802.11 family which is commonly used for the Wireless Local Area Network (WLAN) and it is

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owned by the Wi-Fi Alliance which is formed in the year of 1999 (Nagata & Kojima & Hiraguri & Takatortf, 2010). It is a substitution and extension to Local Area Network (LAN) like Ethernet (Ishu Gupta & Kaur, 2010). The first WLAN standard, IEEE 802.11 (2.4Ghz) which is published in 1997 is invented by Dr. John O'Sullivan and his team who holding a key patent in Wi-Fi (Chen & Zhengyong, 2013; Omilabu, Olusanya, Adebare, Ibitowa & Longe, 2017). 802.11b standard which can achieve a maximum speed of 11Mbps was approved in 1999 which has replaced the legacy 802.11 standard and then achieved a fast growth of this technology in the market (Sendra & Garcia-Pineda & Turro & Lloret 2011). Wi-Fi is high power consumption wireless technology due to its characteristics like high-speed, high-bandwidth and long-range and it is considered over-design for Wireless Sensor Network (WSN) or smart home network when battery powered wireless home automation devices are required (Rathnayaka & Potdar & Kuruppu, 2011). On the contrary, Wi-Fi is feasible to be implemented in data consuming home systems like Artificial Intelligence Voice Assistant, Internet Protocol Closed Circuit Television (IP-CCTV), Internet Protocol Television (IPTV), internet radio, internet music players and Intercom over Internet Protocol (IOIP).

Bluetooth Wireless Technology (1998)

Like Wi-Fi, Bluetooth is another wireless short-link technology uses 2.4Mhz and it was the first wireless interface used in smart home (Kavitha, 2012). It was originally developed in the year of 1994 by Dr. Jaap Haartsen, a former employee of Ericsson which is a Swedish multinational networking and telecommunications company headquartered in Stockholm (Rodzevski & Forsberg & Kruzela, 2003). Subsequently, Nokia, IBM, Toshiba,

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Intel and Ericsson formed the Bluetooth Special Interest Group (SIG) in 1998. At the same year, first Bluetooth protocol was announced and released to the public (Ferro & Potorti, 2005). Then, it has been approved by IEEE Standard Board with 802.15.1 standard in 2002 (Omilabu, Olusanya, Adebare, Ibitowa & Longe, 2017). Bluetooth is a short-range wireless technology which intended to remove cabling of Personal Area Network (PAN) without using more power than a cable. it has many advantages like low-power, low cost and high data rate (Omojokun, 2015). But, Bluetooth is still incompetent to be widely used in the home automation industry due to its architecture scalability constrains, co-channel interference (CCI) and device discovery issue which can delay up to 10.24 seconds before being discovered and data transmission started (Shorey & Miller, 2000). Bluetooth is not suitable to build smart home network as its architecture only afford to accommodate maximum eight devices under an ad hoc network called Piconet. The design of Bluetooth is not intended for low voltage networks, which severely restrict its distribution in Wireless Sensor Network (WSN) (Al Hadidi & Al Azzeh & Tkalich & Odarchenko & Gnatyuk & Khokhlachova, 2017).

Z-Wave Wireless Protocol (2001)

Z-Wave is a proprietary Wireless Sensor Network (WSN) protocol for home automation which theoretically can support maximum 232 nodes in a single network and range up to 100 meters for signal transmission between nodes (Buratti, Conti, Dardari & Verdone, 2009). Z-Wave was developed by Zensys, a Danish company and started introducing to the public in the year of 2001. It is 70% lower in cost compare to Radio Frequency (RF) wireless technology of X10. (Z-Wave, 2011). Z-Wave Alliance has been

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formed in 2005 to promote the Z-Wave technology aiming for residential and light commercial environments (Gomez & Paradells, 2010). The company later acquired by Sigma Designs in 2008 (Zensys, 2009). Most Recently, Sigma Designs sold Z-Wave technology and its business assets to Silicon Labs in 2018 (Sigma Designs, 2018; Silicon Labs, 2018)., Z-Wave Alliance consists of 700 companies from all over the world, 3000 interoperable products and 100 million products sold as of 19th of July 2019 according to their official website.

Zigbee Wireless Protocol (2004)

However, a rival technology called Zigbee which is very similar to Z-Wave on the macro level and it is an open standard with slightly looser certification process. Theoretically it can support maximum 653356 nodes in a single network and signal transmission range up to 100 meters which is the same with Z-Wave (Ramya, Shanmugaraj & Prabakaran, 2011). Zigbee Alliance has been formed in the year of 2002 to develop, maintain and promote Zigbee technology to the world (Adams, (2006). Zigbee Alliance has published its Zigbee open-standard wireless protocol in the year of 2004 and claimed to offer simplest implementation and highest interoperability (Omojokun, 2015). Zigbee Alliance consists of 300 companies worldwide, 3000 certified products and 500 million products sold as of 22th July 2019 which is about one third of current Wireless Sensor Network (WSN) chipset market, and it is projected to hit 1 billion Zigbee chips shipping worldwide annually by 2023 (Zigbee Alliance, 2019).

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Near-Field Communication (NFC) Wireless Standard (2004)

Near-Field Communication (NFC) is a technology developed by NFC Forum, a group established in the year of 2004 by Nokia, Philips and Sony aim to enable data exchange connection between one powered object (NFC reader/writer) and another unpowered or semi-powered object (NFC tags) less than 10cm apart based on Radio Frequency Identification (RFID) technology family which first patented by Charles Walton in 1983 (Walton, 1983; Triantafyllou, Sarigiannidis & Lagkas, 2018). NFC operates on the frequency band of 13.56MHz at a maximum speed of 420kbps which is more than enough to instantly authenticate and identify a smart tag and then unlock the electric magnetic access control locks and the digital smart door locks (Triantafyllou, Sarigiannidis & Lagkas, 2018).

Insteon Protocol (2005)

Practically, switches and sockets are embedded in walls and located close to large appliances or in the extremities area, wireless communication performance and reliability always being degraded due to interference. Hence, Powerline Communication (PLC) based home automation protocols are widely developed since 1970s and it is still trending today (Barker, Irwin & Shenoy, 2017). Smartlabs developed Insteon in the year of 2005 following X10 and UPB (Washington Post, 2005). Maximum network size of Insteon is 256 devices and its messages are broadcasted over its integrated dual-mesh network which formed by combining both Radio Frequency (RF) wireless technology and house's existing electrical wiring (Karimov, 2016). Insteon is a more mature home automation technology compare to X10 and it extends the original X10 protocol with more bandwidth and greater

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reliability as every message listened by receivers is confirmed by sending acknowledgements upon receipt. (Barker, Irwin & Shenoy, 2017).

Comparison of Z-Wave, Zigbee and Insteon

Z-Wave and Zigbee are prominent Wireless Sensor Network (WSN) in the industry, they are similar in many ways like both are using mesh topology and they are designed with low-power consumption architecture (Kavitha, 2012). Z-Wave is very focused for home use while Zigbee not only concentrating on home automation but also military security and environmental monitoring (Grover & Sharma, 2016). In comparison, Z-Wave provides lower data rate than Zigbee but Zigbee network has lower latency than Z-Wave network and Z-Wave is inexpensive compare to Zigbee (O Morales, Joshua & Lopez, Nicole Angelyn & Parado & Pasaoa, 2016). On top of that, Insteon target the same market as Z-Wave do which is focused mainly on residential buildings. Unlike Z-Wave and Zigbee, Insteon does not require a network controller as it uses peer-to-peer communication and hence routing is not required. Insteon uses Radio Frequency (RF) wireless and building's existing electrical wires while Z-Wave is based on mesh-networked transmitters and repeaters. Both Insteon and Z-Wave are claimed that they are better than Zigbee for residential uses (Geer, 2005).

6LoWPAN Standard (2007)

The highly regarded General-Purpose Technology (GPT), Internet Protocol (IP) which began to penetrate major societies since the early 1990s and it is an important technology which operation of a modern society would stop functioning if without it

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(Naughton, 2016). The 6LoWPAN is a concept to implement IP to small devices and its name 6LoWPAN is the result of combining both terms IPv6 and low power Wireless Personal Area Network (WPAN) (Mulligan, (2007). 6LoWPAN is a solution of integrating low-power network as adaption layer based on IEEE 802.15.4 standard into network protocol stack Internet Protocol version 6 (IPv6) (Le, Loo, Lasebae, Aiash & Luo, 2012). The genesis of 6LoWPAN standards, RFC 4919 and RFC 4944 are the first two 6LoWPAN specifications were published to the public in the year of 2007 and it has specified the 6LoWPAN requirements and objectives while the latter standards presents its format and functionalities such as RFC 7668 for IPv6 over Bluetooth Low Energy (Bluetooth LE) (Le, Loo, Lasebae, Aiash & Luo, 2012).

Bluetooth Low Energy Technology (Bluetooth LE / BLE) (October 2010)

Bluetooth LE (also known as BLE in short) has been including in the Bluetooth Core Specification version 4.0 which is completed by Bluetooth Special Interest Group (SIG) in 2010 and commonly marketed as Bluetooth Smart (Darroudi & Gomez, 2017). The Health Thermometer Profile and the Heart Rate Profile in Bluetooth 4.0, this will give rise to wireless devices that can help monitor and send health information from biomedical sensors to smart-phones and central monitoring systems (Yu, Xu & Li, 2012). As a WPAN technology, BLE is fit for medical and health monitoring use as it is readily equipped by variety of smartphones and commonly compatible with smart gadgets like smart wristband and smart watches (Furst, Chen, Kim & Bonnet, 2018). But it is not feasible to be used for Wireless Home Automation Network (WHANS) due to its limitations like short range coverage and disadvantages of star network topology (Siekkinen, Hiienkari, Nurminen &

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Nieminen, 2012). WHANS usually required mesh topology for better reliability by allowing most data transmission to be distributed even if any of the devices offline, failed node must not cause a break in the network (Karimov, 2016). Hence, Insteon, Z-Wave, Zigbee and Thread which based on mesh network are more suitable to be used in WHANS (Darroudi & Gomez, 2017). Consecutively, Bluetooth 4.1 specification was released in 2013 to cope with the limitations of BLE by incorporating mesh network support to its fundamental and now the slave devices are allowed to connect more than one master node simultaneously thus the original BLE star network can be extended to a kind of mesh network which is self-organizing, self-healing and enables path diversity. (Baert & Rossey & Shahid & Hoebeke, 2018). 6LowWPAN was integrated through the Internet Protocol Support Profile by BLE from Bluetooth version 4.2 onward (Marksteiner, Jimenez, Valiant & Zeiner, 2017). Nevertheless, the structure and model for building and developing a BLE mesh network are not specified in the Bluetooth 4.1 standard and its following versions like 4.2 and 5.0 also do not provide further functionality until Bluetooth Mesh Networking protocol being published (Darroudi & Gomez, 2017).

EnOcean Wireless Technology (March 2012)

EnOcean is the world's first international battery-free wireless standard (ISO/IEC 14543-3-310) for Wireless Sensor Network (WSN) in building automation which is using innovative energy-harvesting approach based on ultra-low power electronics (Li & Hong, 2014). Imagine that, the magic happens when you press on a button of a wireless and battery-less on-wall switch, electricity generated instantly due to your motion which is just enough to activate the EnOcean Radio Frequency (RF) wireless module and to transmit the

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control command to a sensor located maximum 30 meters away in order to remotely turn on a connected light or a home appliances. EnOcean module generate electricity by converting kinetic energy from mechanical motions, thermal energy from temperature differences and solar energy from light sources (Ploennigs & Kabitzsch, 2010). EnOcean used piezoelectric to generate electricity from pressure initially but were later replaced by electromagnetic energy sources to securely transmits its data over 315Mhz (US) or 868Mhz (EU) via Radio Frequency (RF) at 125Kbps data rate (Withanage, Yuen & Otto, 2014). The super simple installation method as no wire is required and its much-reduced sensor node size are the main advantages of using EnOcean technology (Lopez Iturri & Celaya-Echarri & Azpilicueta & Aguirre & Astrain & Villadangos & Falcone, 2018). EnOcean is a simple but feature rich technology which capable to handle ad-hoc network topologies at the same time remained flexibility of wireless devices and removed the cost of battery replacement maintenance tasks (Ploennigs, Ryssel & Kabitzsch, 2010).

Thread Wireless Protocol (2015)

Like Bluetooth Low Energy (BLE), Thread is also an open standard IEEE 802.15.4 based 2.4Ghz mesh networking technology uses 6LoWPAN wireless protocol and its protocol is maintaining, defining and standardized by Thread Group in the year of 2014 and released in the year of 2015 (Ravirajan, 2016). Thread Group is an alliance of a working group by more than 200 companies like Nest Labs (a subsidiary of Alphabet, the parent company of Google), Samsung, ARM Holdings, Qualcomm, Silicon Labs, Somfy, Osram, Yale and others (Dragomir, Gheorghe, Costea & Radovici, 2016). Thread protocol concentrates only on the Internet Protocol version 6 (IPv6) but Border Router (gateway)

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enabled its backward compatibility with IPv4 which is the most commonly used internet protocol nowadays (Ravirajan, 2016). Thread has a line-of-sign range of 100 meters under ideal condition and able to accommodate more than 250 devices in a single network (O Morales & Lopez & Parado & Pasaoa, 2016). Like Wi-Fi, Thread protocol refer to the networking layer only, it can be used in various applications such as home automation and it does not require proprietary gateway thanks to 6LoWPAN unless interconnection with other technologies needed which can be done in the application layer through integrations in a network hub (Cilfone, Davoli, Belli & Ferrari, 2019). Thread is an important component in Google's Internet of Things (IoT) solutions besides Brillo (an Android based IoT operating system) and Waeve (a secure and reliable backbone application layer network for Google Nest products) (Ravirajan, 2016).

Bluetooth Mesh Wireless Protocol (2017)

Following the release of Google's Thread protocol, "Bluetooth Smart Mesh Working Group" was formed by Bluetooth Special Interest Group (Bluetooth SIG) announced in a press release which issued in the year of 2015 and its main purpose is to design a BLE-based architecture with mesh topology (Darroudi & Gomez, 2017). In the year of 2017, The SIG announced that Bluetooth began to fully support mesh network by Bluetooth Mesh protocol (Darroudi & Gomez, 2017). It removed the limitations of range coverage with new maximum up to 750m (Digi-Key, 2017) and Piconet network size by allowing maximum 126 hops and supporting up to 32767 nodes in a single network (Wan & Liu, 2018). Bluetooth Mesh has opened the door to the world of Internet of Things (IoT) but the technology in its current state is not suited to implement a mesh network consisting

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of solely power limited nodes as it is clearly focuses on non-power limited nodes, e.g., smart lighting, to construct the backbone of the mesh network, with the possibility to add power limited nodes to an existing network if needed (Baert & Rossey & Shahid & Hoebeke, 2018).

Comparison of Thread and BLE Mesh

Both Thread and BLE Mesh are two of the newest wireless mesh network protocols which using 2.4MHz spectrum like Zigbee (Digi-Key, 2017). BLE Mesh has outperformed Thread in transmission range with 750m in a single hop and maximum data rate up to 2Mbps while Thread only has 100m range and maximum 250kbps (Digi-Key, 2017). BLE Mesh has advantage of mobile infrastructure readiness through smartphones equipped Bluetooth version 4.0 at least, while Thread only has very few as it is still new (Digi-Key, 2017). BLE Mesh is not supporting Internet Protocol version 6 (IPV6) yet but Thread did as it is based on 6LoWPAN and networking performance wise, Thread is relatively more efficient as it is fully routed and while BLE Mesh only with managed flooding (Silicon Labs, 2018). BLE Mesh and Thread are performed similarly in lab tests when the network size is small (24 nodes) but Thread stand out with better throughput and lower latency when network size increased to medium (up to 96 nodes) while BLE Mesh experienced largest increase in this case, and finally BLE Mesh is totally being knocked down in the round with large network (up to 192 nodes) due to its managed flooding method while Thread is fully routed (Silicon Labs, 2018). There is no winner at this moment as each protocol has its own merits when using for home automation in smart home environment which usually only small network is needed.

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History of Smart Home

Second Industrial Revolution - Electrification (1870)

Electrification process has been accelerated during Second Industrial Revolution which is also known as Technological Revolution has started from 1870 (Mokyr & Strotz, 2000). A home equipped with electrify appliances is considered smart in the early of 20th century and it was promising consumers more time for leisure activities with home automation (Barlow, 1999). Home automation is defined as the automation technology applied in a home which is designed to automate housework and household activities (Jacobsson & Carlsson, 2016; Wang, Zhang, Zhang, Zhang & Li, 2013). Automation is a time-saving technology which shifts manual-mechanisms to machine-mechanisms (Pathak, Kulkarni, Karandikar, Kharwadkar, 2018).

Electrical Home Appliances (1900-1930)

Electrification has popularized the use of home appliances and its adoption started to grow rapidly in the mid-1920s due to the right conditions of cheap electricity supply and reliable distribution of electrical wiring system (Adrian Forty, 1986). Variety of home appliances have been invented during the year of 1901 to 1930 (James Barlow, 1999). For instance, Hubert Cecil Booth invented the first electric vacuum cleaner in 1901, Earl Richardson invented the first lightweight electric iron in 1903 and Charles Strite invented the first electric modern timed pop-up toaster in 1919 (George Constable, 2003). Then, American Fred W. Wolf invented the first electric refrigerator for domestic use in 1913,

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followed by John W. Hammes invented the first electric garbage disposal in 1927 because he wants to make kitchen cleanup work easier for his wife and John W. Chamberlain invented first automatic washing machine in 1930 which can wash, rinse and extract water from clothes (George Constable, 2003). More than 70% of the US families have acquired and adopted electrify time-saving home appliances in 1960 (Bowden & Offer, 1994). Smart home with home automation by machines which powered by electricity that replaced labor force truly made people's life easier, relaxing and it also allowed them to enjoy life and having more quality time with family (Pérez, 2012).

The World's First Electric Garage Door (1926)

The electric garage door opener is a classic example of motorized systems for domestic use. It was invented by C.G. Johnson in 1926 and did not being widely used until it paired with a key operated switch located on a post beside the driveway which designed by Era Meter Company (Popular Science, 1946). The technology has further developed with added wireless remote-control feature by radio signals (Popular Science, 1931). Automatic garage doors are the largest moving object at home; hence its safety must be ensured with sensors by providing features like emergency stop quick-release mechanism and automatic reverse when bumped on an object (United Stated Consumer Product Safety Commission, 2004). The concept of electric garage door with motors has laid a foundation for later developments of motorized systems for awning, blinds and curtains.

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ECHO IV: The World's First Smart Home Computer (1966)

Engineer Jim Sutherland invented the first computerized home automation device namely ECHO IV (Electronic Computing Home Operator) in the year of 1966 (Tomayko, James, 1994). It was a hand-crafted system with surplus electronic parts and enclosed in a walnut wooden cabinetry. ECHO IV is designed to computerize many of the household chores like shopping list of groceries tracking, home appliances controls with temperature detections and weather prediction feature.

Honeywell Kitchen Computer (1969)

Three years later, Honeywell company following the idea of ECHO IV and then created an amazingly beautiful computer in 1969 dedicated for housewife which to be used in kitchen and with a price tag of over $10,000 USD (Stein, 2011). Unfortunately, both ECHO IV and Honeywell Kitchen Computer were never commercially sold a single unit, but they were the implementation of this brilliant home automation idea and they have kickstarted the revolutionary concept of modern smart home systems (Spicer, 2000).

Crestron: The Pioneer of Home Automation Industry (1969)

Crestron was founded by George Feldstein in the year of 1969 when he was fired by his ex-employer and he work on his own alone until 1973 the first employee was hire (Kayye, 2014). Crestron has earned huge success in 1990 with 100 employees and $5 million sales a year selling all-in-one system of integrated audio amplifiers, video matrixes and lighting control for homes and companies (Ewalt, 2011). The Crestron controllers get inputs different audio-visual sources and distribute according to needs of every areas,

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rooms or zones without quality reduction together with lighting control automations (Lobaccaro & Carlucci & Löfström, 2016).

National American Association of House Builders (NAHB)'s "Smart Home" (1984)

The enormous success of X10 in home automation and home security has proved the concept smart home which certainly brought benefits to the users and it has drawn attentions from construction industry. The term "smart home" was first officially used by the National American Association of House Builders (NAHB) in 1984 to encourage the inclusion of the necessary technologies into the design of new houses (Harper, 2003; Madakam & Ramaswamy, 2014). It is a home of the future concept which sharing a similar concept with automated home, intelligent home, interactive home, aware home, integrated home and connected home (Friedewald, Costa, Punie, Alahuhta & Heinonen, 2005). The internet has kicked started peer-to-peer (P2P)

LG Electronics: The World's First Internet Refrigerator (2000)

The world's first internet enabled home appliance is LG Internet DIOS launched in the year of 2000, an internet connected refrigerator with touchscreen, electronic pen, webcam and sensors, which was a $49.2 million USD technology which started research and development from 1997 by a team of 55 researchers from LG (Madakam & Ramaswamy & Tripathi, 2015).

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iRobot Roomba: The World's First Home Vacuum Cleaner Robot (2002)

The world's first home robot was born in the year of 1984, HERO Jr. (RT-1). It was a smaller version of a commercial robot named HERO 1 (ET-18) (Robillart, 1983). HERO Jr. is less complex which equipped with an onboard speech synthesis, a range sensor, a light sensor and a sound sensor (Boyet, 1985). Followed by another similar robot named Topo which started to be sold commercially in early 1983 (Androbot, 1983). Those programmable autonomous robots which make around 1980s were designed to provide entertainment and a little bit on education, they are not smart enough for domestic house chores until the born of iRobot Roomba, an autonomous home vacuum cleaner (iRobot, 2012). It is an intelligent robot which running on algorithms based on a set of sensors for the purposes like navigation within the work areas in order to detect obstacles, dirty spots and avoid itself from falling downstairs (iRobot, 2002). Based on the similar technologies, iRobot launched Scooba, a floor washing robot in 2005 and Dirt Dog, a floor sweeping robot in 2006, following the success of Roomba (iRobot, 2012).

Control4: The Most Popular Home Automation Operating System (2003)

Control4 is one of the most popular home automation platforms selling proprietary controllers, touchscreen hubs, light switches, scene remote controllers, thermostats, locks, cameras, sensors, speakers and networking equipment with 5900 system integrators in over 100 countries (Control4, 2003). It was founded in the year of 2003 and aimed to make their platform become smart home operating system by enabling interoperability between different communication protocols like Wi-Fi, Bluetooth, Z-Wave and Zigbee for more than 13,500 third party consumer electronic products (Jacobson, 2014). Cisco, a

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multinational networking conglomerates backed Control4 for its energy management feature which they intended to use it to increase energy efficiency of smart homes in smart cities (Lamonica, 2015). Control4 eased the integration processes seamlessly by implementing automatic discovery feature using Simple Device Discovery Protocol (SDDP) in their network and this has concluded as one of the success factors of their business model (Jacobson, 2014).

Ecobee: The World's First Smart Thermostat (2007)

The first generation of ecobee was born when the its founder, Stuart Lombard trying to save his home electricity bill with a programmable thermostat but failed as it was difficult to be configured even by a technical professional like him and hence, he decided to make one for himself which is smarter in delivering comfort and at the same time conserving energy for better electricity bill saving (ecobee, 2007). Ecobee is a thermostat that equipped with automatic scheduler, sensors and internet accessibility which empowering it with forecast ability which powered by artificial intelligence in the cloud (Rau, Gong, Huang & Wen, 2016). It optimizes energy usage with algorithms by leveraging the comfortability over outdoor weather and number of users (Bustamante, Castro, Laso, Manana & Arroyo, 2017). In 2017, the fourth generation ecobee smart thermostat has been further enhanced in term of it intelligent by integrating with Alexa voice service which powered by artificial intelligence (AI) (Business Wire, 2017).

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Samsung: The World's First Smart Television (TV) (2008)

Do not confuse smart television (TV) with Internet Protocol TV (IPTV) and Web TV, they are totally different things in term of technology level. Smart TV is a combination of hardware makers (TV), software developers (TV operating system) and content providers (videos and music producers) with smart features like internet browsing, screen sharing, video callings and able to be controlled via a smartphone APP (Yusufov & Kornilov, 2013). Samsung was launched the world's first smart TV in the year of 2008 (Jones, 2012).

Google Nest (2010)

Nest is a brand name for a smart thermostat launched in 2011 which is Wi-Fi enabled, smartphone APP-enabled, sensor-driven and self-learning, originally was owned by Nest Labs, a company co-founded in 2010 by Apple ex-employee, Ton Fadell (Levy, 2013). Nest thermostat is smart because it learns from human behaviors, anticipate user's needs and adjust temperature accordingly (Wollerton, 2018). After two years in 2013, Nest launched its second product which it was claimed as a better smoke and carbon monoxide detector with internet accessibility and artificial intelligence built-in (Patel, 2013). In the same year 2013, Nest was acquired by Google with $3.2 billion USD in order to strengthen its presence in home appliance industry (Trefis Team, 2014). As of February 2018, Google Nest said they have sold over 11 million devices since 2011 (Wollerton, 2018).

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If This Then That (IFTTT): Conditional Automation Platform (December 2010)

If This Then That (IFTTT) is a provider of free web-based task automation services with configurable conditions and variety of reactions through Application Protocol Interface (API) of third-party software (Ovadia, S., 2014). It is a totally software-based automation system founded in 2010 by Linden Tibbets which constantly monitor the pre-set conditional inputs from a hardware like a smartphone or a software like notifications from Facebook or triggers from Internet of Things (IoT) smart home sensors, and then react to it via another software with further actions like sending an email using Gmail or via hardware like switching on an air conditioner, turning on a lamp and changing the color of a lightbulb (Vorapojpisut, 2015). IFTTT joined the space of Internet of Things (IoT) in 2012, by interacting the physical world for the first time through integrations with Belkin Wemo devices (TNW, 2012).

Windoro: The World's First Home Windows and Glass Cleaning Robot (2011)

Glass cleaning works at high place are dangerous, one of the best ways to minimize risks and to avoid accident are using robots. Similar to the concept of floor cleaning robot, a glass cleaning robot consists of three elements which are navigation unit, cleaning unit and a dedicated adhering unit which Windoro uses four magnet sets which paired with inner-units on the robots and outer-units on another surface of the glass, instead of using traditional suction method. This robot must be enhanced as it does not equip with Internet of Things (IoT) capability and not connected to the cloud for monitor and control purpose (Young-Ho Choi & Kwang-Mok Jung, 2011).

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Lockitron: The World's First iPhone Controlled Wi-Fi Smart Door Lock (2011)

Lockitron is a brand of modern smart door lock which can be unlocked using an iPhone APP via Bluetooth, and NFC without sacrifice your traditional metal keys (Grove, 2011). Apigy Inc. company, the manufacturer of Lockitron originally announced the first version in the year of 2011 and then the enhanced version in 2012 with Internet of Things (IoT) capability like Bluetooth Low Energy (BLE) integration, Wi-Fi connectivity and unlock with virtual keys which can be distributed over the internet or a SMS (Osborne, 2012; Goode, 2012). Lockitron considered as a pioneer in IoT smart digital door lock era as it was provided with Application Protocol Interface (API) for integrations with other smart products and IoT platforms for advanced home automation purposes (Thiebaud, 2013; Cameron, 2014).

Belkin Wemo: The World's First Wi-Fi Power-Plug (January 2012)

Belkin, a well-known consumer electronics manufacturing company who specialize in making connectivity devices came into the home automation business, announced a Wi-Fi based power-plug in January of 2012 before any of the technology leaders like Apple, Google and Amazon. The Wemo power plug were only able to be controlled with iPhone, iPod and iPad APP until 2013, Belkin announced the support for Android OS in Consumer Electronics Show (CES) and it has attracted huge interest regarding the capability of smartphones smart home controls after they demoed their home automation product line (Manish Prakash Gupta, Neha Shrivastava, 2018).

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Samsung SmartThings: The World's First DIY Wireless Smart Home Hub (2012)

Unlike the home automation hubs by Crestron and Control4 which need professionals for installations, setup and automation programming. SmartThings is a first-of-its-kind platform which consists of a hub (gateway), a cloud platform and a set of Application Protocol Interface (API) for integration which allow communications between home objects such as lightbulbs, door locks, TV, sensors, refrigerators and even sprinklers using a smartphone APP (Frizell, 2014). SmartThings hub has no port for any wired home automation connection except LAN port for internet access, it supports wireless Z-Wave and Zigbee protocols for connections of variety of home automation devices (Samsung SmartThings, 2019). SmartThings has been acquired by Samsung in order to enlarge its territory in home automation industry (Samsung, 2014).

Philips Hue: The World's First iOS-based Lighting Control System (October 2012)

Philips Hue is a lighting control system with color-changing light-emitting diode (LED) bulbs based on Zigbee wireless technology which was released in October 2012 (Philips, 2012). It is exclusively sold only in Apple Store for Apple users. The bulbs can be grouped, monitored and controlled using an iOS APP and its home automation features have been further extended via Apple HomeKit integrations in 2015 (CNET, 2015).

Ring: The World's First Battery-Powered Wireless Video Doorbell (2013)

Ring was founded in the year of 2013 which formerly known as DoorBot who was crowdfunded for the reinvention of traditional doorbell by giving it wireless internet

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connectivity, High-definition (HD) video camera and Passive Infrared (PIR) motion sensor, it will instantly notify house owner allow via APP when visitor detected, enable video intercom when the doorbell pressed and all these are powered by battery solely (Siminoff, 2014). Recently, Ring was acquired by the maker of intelligent voice assistant, Amazon with around $1.2 billion USD in 2018 (Kim, 2018).

NETGEAR Arlo : The World's First Battery-Powered Wireless Security Camera (November 2014)

The world's first Closed-Circuit Television (CCTV) video surveillance system was installed to observe V-2 rocket launchings by Siemens AG company in the year of 1942 (Dornberger & Walter, 1954). CCTV usage was not widespread until around 1970s when a cheaper technology named Videocassette Recorder (VCR) was invented (Kruegle & Herman, 2011). New York was the world's first city to fight crime with CCTV since 1968 (Robb & Gary, 1979). Over 50 years of smart home technology development, security camera nowadays are able to record High-Definition (HD), store video footages on the cloud and stream real-time videos to multiple users simultaneously with smartphone APP. NETGEAR, a networking hardware maker announced Arlo, the world's first battery-powered wireless smart home security camera with integrated motion sensing and night-vision capabilities (NETGEAR, 2014).

Amazon Echo: The World's First Intelligent Home Assistant (November 2014)

Voice activated virtual assistant technology was kick-started by International Business Machines (IBM) company with the introduction of world's first digital speech

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recognition tool in the year of 1961 (Voicebot, 2018). In 2011, Apple Inc brought virtual assistant technology to its iPhones and this is the first time in the human history that virtual assistant was integrated with mobile phone Operating System (OS) and it was followed by Google with Google Now (was renamed to Google Assistant in 2016) on Android OS in 2012 (Macrumors, 2011; CNET, 2012). Amazon company, a game changer of virtual assistant technologies who developed a smart speaker in 2014 which built-in with standalone virtual assistant powered by artificial intelligent in the cloud and it has eased for more natural communications between human and machines which added a new way of home automation controls in modern smart homes (Reuters, 2014; iMore, 2015). Two years later, Google released its own smart home voice assistant to chase Amazon in 2016 (John Dye, 2016).

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