Interreg
EUROPEAN UNION
2 Seas Mers Zeeën
INCASE
European Regional Development Fund

Smart Buildings: Communication, Control, Ergonomic HMI & IoT Integration

A short overview of key technologies, challenges and future opportunities

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The INTERREG project INCASE is partially funded by the European Union, through the INTERREG Va 2 SEAS program (2014-2020).

The Belgian project partners are partially funded by the Provinces of East-Flanders and West-Flanders.

This report is developed by the INCASE project partners:

Version November 2017

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The INCASE project

Industry 4.0 (I4.0) is the next industrial revolution. Manufacturers are focussing on client-specific production and added-value products. In Germany 84% of the companies feel the pressure to digitize and 57% will significantly change their business model due to the digital revolution. Germany is world leader in this revolution. The project main objective is to ***close the gap between the 2 Seas region and Germany & other leading countries***, by developing and demonstrating the necessary key technologies towards companies, in this way facilitating the conversion towards I4.0.

INCASE develops knowledge, innovative applications and pilots on key enabling automation technologies for the future I4.0. INCASE will deliver ***10 thematic demonstration trajectories*** on those key enabling automation technologies for smart factories and green technologies for smart homes and factories. The demonstration actions will inspire practicing engineers towards new products and new production methodologies. The intermediary organizations will actively create awareness on the future I4.0.

The project contains ***three main workpackages***. ***WP1*** develops pilots on key enabling automation technologies for Industry 4.0, to achieve an early market uptake by and increased awareness of the manufacturing industries. Involved technologies are Industrial Communication (Profinet, Power Line Communication, ProfiCloud, Networked Control) and Integrated Design (Mobile robotics, Industrial Hardware Targets, Cosimulation). ***WP2*** develops pilots to reduce energy consumption in both home automation and industrial automation, and increase the awareness & knowledge for the automation and manufacturing industries. Involved technologies are Communication and HMI technologies for smart factories and smart houses (ProfiEnergy, Power Line Communication for smartgrids, Control & HMI for Smart Houses, energy monitoring devices connected to the Internet of Things). ***WP3*** develops demonstration tools, based on the pilots, to perform numerous demonstration actions for practicing engineers in industry. In this way the knowledge on new technologies is increased and an early market uptake of Industry 4.0's new automation technologies is achieved in the 2 Seas region.

The ***main objective*** of INCASE is preparing the industry (automation & manufacturing industry) for the future "Industry 4.0" (I4.0) and "Industrial Internet of Things" (IIoT). This is done by:

- Creating awareness of technical management and decision makers of companies on the possibilities of the new technologies.
- Preparing practicing engineers by demonstrating new technologies for the future smart interconnected factories, smart buildings and sustainable engineering.

The project ***specific objectives*** are:

- Pilots on ProfiCloud
- Pilots on Stress-testing on Profinet
- Feasibility study on PLC
- Pilots on Networked Control
- Pilots on Integrated Design
- Pilots for ProfiEnergy
- Pilots for smartgrids using PLC
- Pilots for Control&HMI for Smart homes
- Pilots for energy monitoring devices connected to IOT, IIOT and industrial networks
- Demonstration tools & actions

This project has received funding from the Interreg 2 Seas programme 2014-2020 co-funded by the European Regional Development Fund under subsidy contract No 2S01-049.

1. Introduction

INCASE (towards INdustry 4.0 via Networked Control Applications and Sustainable Engineering) aims at designing and implementing sustainable engineering pilots, using the new and emerging key automation technologies for the future factories and buildings, in order to increase market introduction, and thus resulting in decreased energy consumption. The rationale behind having two quite different domains, factories and buildings in the same work package is that cross-fertilization could bring up new ideas and solutions.
As an early step toward this goal, the involved partners worked on a series of detailed reports covering essential aspects and technologies for smart buildings. This document summarizes these reports and gives the reader an overview of smart buildings, the key technologies involved, the challenges and the future opportunities, from the viewpoint of the developed pilots at the involved partners institutes. Additionally to the description of technologies, cases are given, developed on site of the involved partners.

The report is arranged in the following chapters. Chapter 2 gives an introduction to smart buildings. Chapter 3 focusses on the basics of communication, chapter 4 discusses the technologies for communication which are relevant for smart buildings. A case on RF-communication as low-cost alternative is added. Chapter 5 introduces Human-Machine Interaction (HMI) and control, with emphasis on Machine Learning. A case on voice control, combined with a home automation platform (HAP) is added. Chapter 6 finally discusses shortly the economic relevance and user impact.

2. Smart buildings: Challenges and Opportunities

2.1. Smart buildings

Communication with buildings has historically been done using copper-wired telephone networks with the help of Private Automatic Branch eXchange and MODEMs equipment. One of the world's most successful online services accessible through telephone lines has been launched in France in the beginning of the eighties. Offering a Videotex online service this was called *The Minitel*. Ten years later Internet and especially the World Wide Web (WWW) offered new possibilities of interaction. The launch of the Smartphones in 2007 represents the next significant milestone in data communication.

The entry point of Internet in buildings is in many cases still done using DSL lines on public or private telephone wired networks. Very dense or urban areas may also have high-speed communication through fibre optic or cable networks.

As smartphones and tablets authorized to stream video and music, it became obvious that wireless cellular communication had to adapt to the underlying need of speed. Known as 4G, the fourth-generation of wireless communication for cell phones has been designed to this.

Since a couple of years there are more devices connected to the internet than there are people in the world. These figures[1] are rapidly increasing and connectivity is entering our homes as well. The Internet of Things (IoT) has become a reality. Connected buildings, or smart homes, roughly have functions in two domains: management of energy consumption and comfortable living. Comfortable living can be understood as both assisted living and facilitated living. Buildings in general (residential, commercial, offices, industrial buildings and healthcare facilities) are the largest contributors to global carbon emissions. They account for about 40% of the world's total footprint. Reducing the impact of buildings on global carbon emissions is important to help fight against climate change, but for building owners it is not the only driver. In organizations, after salaries, buildings are one of the biggest operational expenses and energy amounts for a significant part in this.

Making buildings “smart” can serve different needs. The needs can vary depending on the type of the building but generally, it is about allowing a better control and monitoring of the building itself and its inhabitants. For instance, we may have very distinctive use cases:

- security with access controls
- smart HVAC (Heating Ventilation Air Conditioning) management
- smart light management, depending on outdoor daylight and presence of people
- indoor location system
- room management to know the occupancy and the reservations
- energy and water consumption monitoring to watch and detect any leak or unusual

[1] https://www.statista.com/statistics/471264/iot-number-of-connected-devices-worldwide/

consumption
- indoor air quality monitoring
- elderly care monitoring system

New buildings are designed to be more efficient (both energy efficient and user efficient), but obviously most gains will come from retrofitting existing buildings and infrastructures. In recent decades, most buildings (however mainly non-residential) have been equipped with an increasing number of sensors, control systems[2], user-friendly interfaces by communicative panels, touchscreens or similar. Significant energy savings can arise from the use of analytical tools that will help achieve a better integration and orchestration of these disparate and sometimes organically grown building systems.

The rise of the Internet of Things (IoT) opens up opportunities to further enhance these systems by combining them with a very wide variety of brand new kinds of devices ranging from smart appliances to plug energy meters, smart locks, air quality monitors, smart thermostatic valves and so on. Often, these "things" may not have been designed primarily to help saving energy: they may for instance be part of some other system dedicated to safety (air quality monitoring, elderly care alerts, ...), security (access control, window opening detectors, ...), welfare and comfort (smart locks, smart fridge, …) or anything else. Although BAS are acquainted already for a long time, the breakthrough in even new homes is limited. In comparison, smart homes based on the IoT has several advantages, giving an expected breakthrough in short-term. The advantages of the "things" are:

- rather cheap (ready for residential market),
- quite versatile,
- easy to deploy (running on battery and using wireless technologies)
- easy to integrate (Internet ready, able to connect to the cloud)

The additional data they produce are often very helpful to the analytical tools that continuously monitor, manage and control the building, providing the intelligence in the BMS.

2.2. Challenges

Several challenges can be detected. A first one relates to connectivity and integration. Data from existing equipment and building systems (HVAC, lighting, meters, sensors, access control, elevators, BMS, ...) must be remotely accessed, yet these systems tend to be quite diverse (kind, manufacturer, age), use different communication protocols and are often not designed to connect to IT-networks.

Another challenge relates to the cost of retro-fitting an existing building, a cost that may be

[2] Building Management Systems (BMS) and Building Automation Systems (BAS)

significant compared to the expected savings for certain classes of buildings: mainly older, smaller scale or residential buildings, school buildings, buildings lacking proper building systems or technical ceilings, ...

No retrofitting project will however deliver expected savings without the proper involvement of users, occupants, building managers. Therefore, usability is another major challenge for smart building solutions. These tools tend to produce very large volumes of data and it is critical to present only appropriate subsets of it. Moreover, this information must be given in a consumable and actionable form. For the user it has to be easy to understand and the user should easily figure out what to do with the information and how to act. This is of course an HMI issue, dashboards may be used as interfaces, but multi-modal approaches with the addition of text to speech and command or gesture recognition may be in some case more appropriate.

Finally, acceptance by the user is a major non-technical concern. Detection of presence gives privacy issues and can be (mis)used as surveillance method in working environments.

2.3. Future opportunities

Some key technologies may have a significant impact on the rate of adoption of Smart Building solutions by addressing several challenges and mitigating common barriers. As an example, all technologies related to the Internet of Things and in particular standard low power wireless communication will have a deep impact on Smart Buildings, because they have the potential to significantly lower the costs of retro-fitting older and also residential buildings, thus addressing more effectively the Business-to-consumer (B2C) market.

Other technologies may as well have the potential to bring disruptive innovations to the next generation of smart building solutions. Artificial intelligence and machine learning belong to that category, as a result of their ability to combine, correlate, predict and in the end bring value to the vast amount of data produced by smart buildings every day

Smart buildings are not islands, they will be part of the so-called smart cities and smart grids and as such will have to be integrated in bigger systems. Smart buildings will become individual nodes of the smart grid, they actively participate in managing demand and supply in an environment that will include power plants, transmission networks, renewable energy, electric vehicles, ...

2.4. Mindmap

The functionality of smart homes requires a combination of several technologies with different applications. The mindmap[3] (Fig.1) gives an overview of the topics involved in smart

[3] The full mindmap is available on the Incase website.

homes. A definition of domains, where smart applications can be involved can be seen on fig. 2. Specific for HMI, Control and Analysis, the mindmap can be expanded and can be found in fig. 3. Specific for communication, the mindmap can be further expanded into wired and wireless technologies and middleware to connect different technologies (fig. 4).

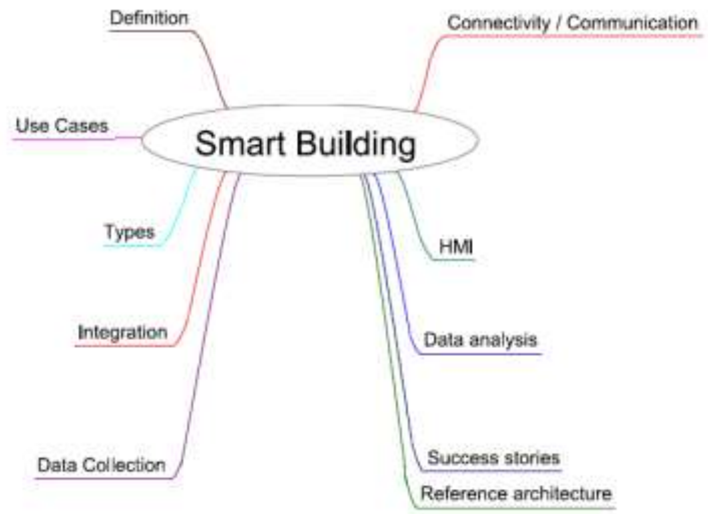

Fig. 1. Mindmap: topics related to smart buildings

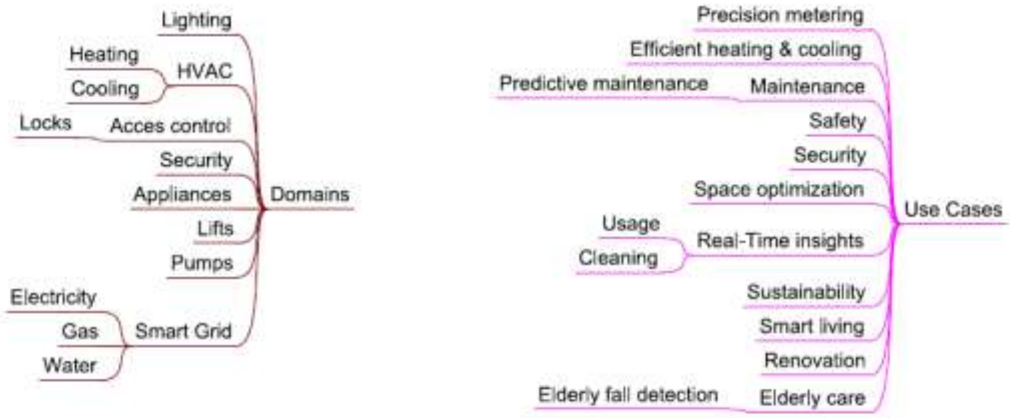

Fig. 2. Domains where to apply smart applications in smart buildings

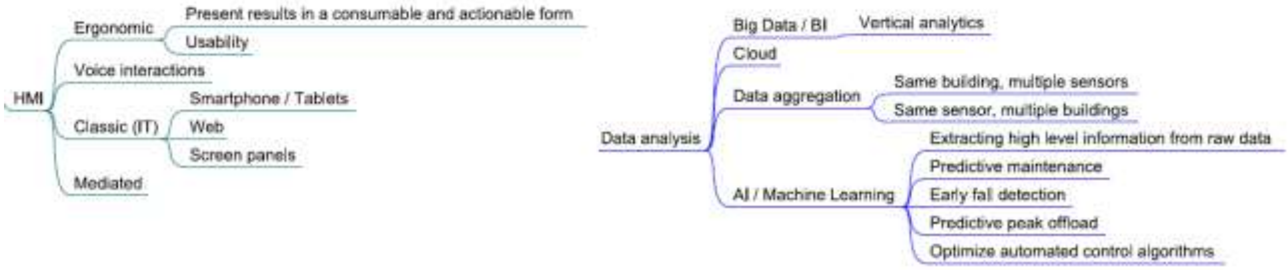

Fig. 3. HMI, Control and Data Analysis related to smart buildings

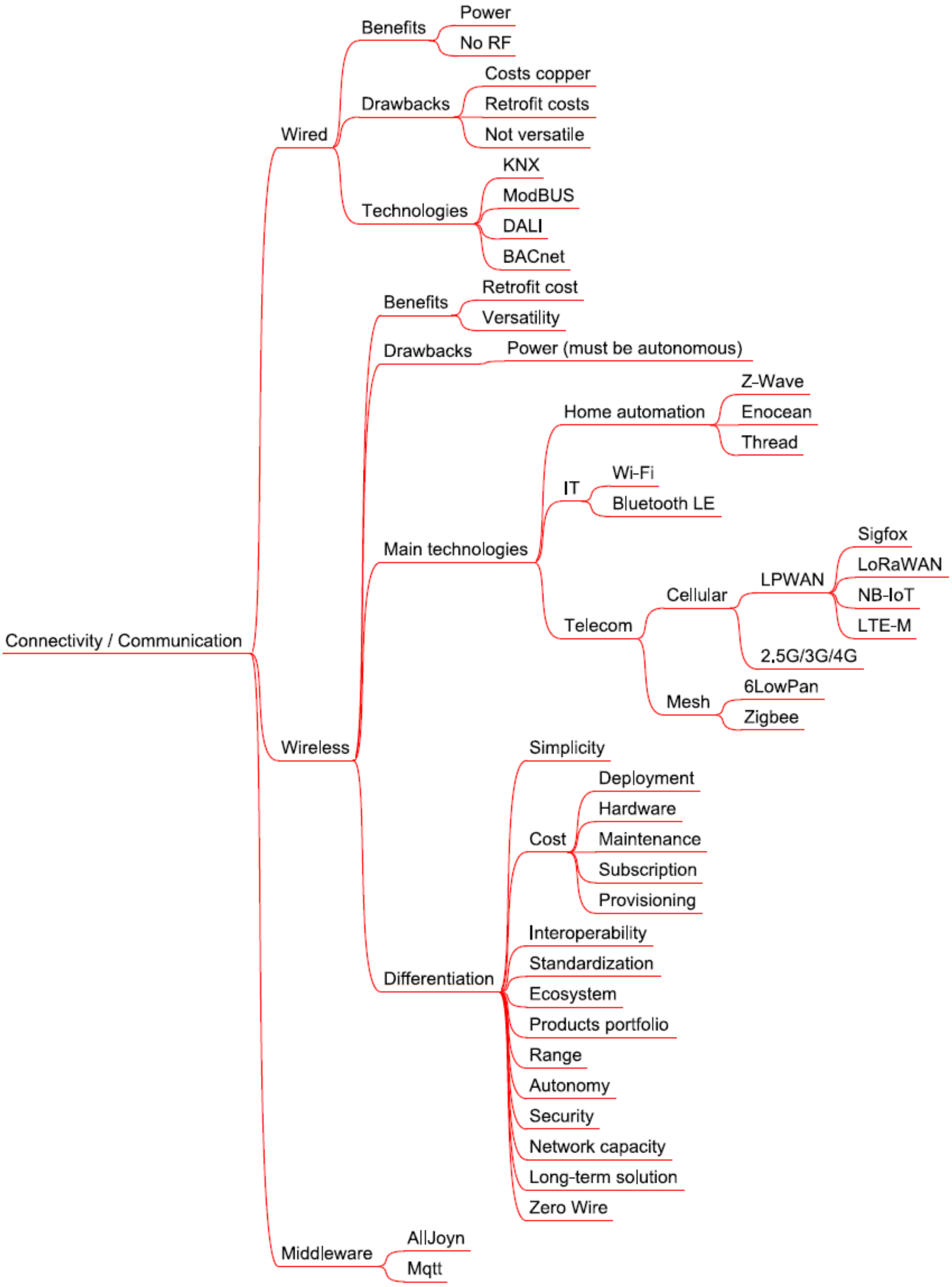

Fig. 4. Expanded mindmap on communication and connectivity for smart buildings

3. Communication

3.1. Smart Buildings

There is a lot of different equipment developed nowadays allowing us to make buildings smart. Actuators, automation and control equipment are a part of it but the fundamental components are the sensors. A lot of sensors are necessary throughout the building in order to be able to collect all the information needed and with the appropriate granularity level. For instance, if we want to manage the temperature, we may need many different temperature sensors to get the data and act accordingly (heat up the room if it is too cold for example). The same applies for instance for the precise measurement of electricity consumption, in which case we need to deploy meters not only at building level, but also at room level and in some cases even at socket level or within equipment and appliances.
On Fig. 5 some examples of equipment are shown (current sensor, air quality monitor, open window detector, thermostatic valve, water leak detector, …). All components use wireless communication technologies and most work by harvesting energy from their environment (solar, heat, mechanical, induction, ...)

Fig. 5. Several wireless sensors and actuators

3.2. Smart Buildings and Wireless technologies

To get the data from the equipment, communication is necessary with the sensors, actuators and automation and control equipment. There are only two possibilities: wired and wireless communication. Running cables through all the building would involve an extremely high deployment cost, especially when retro-fitting an existing building. Additionally, the mobile devices as smartphones and tablets have become the main controller. Therefore, the wireless

technologies are the only alternative and their versatility is a strong advantage.
The final goal would be to use only wireless devices and run them on batteries for years or with harvesting energy from environment.
The different wireless technologies are presented in fig 6, with given operating range and data rate.

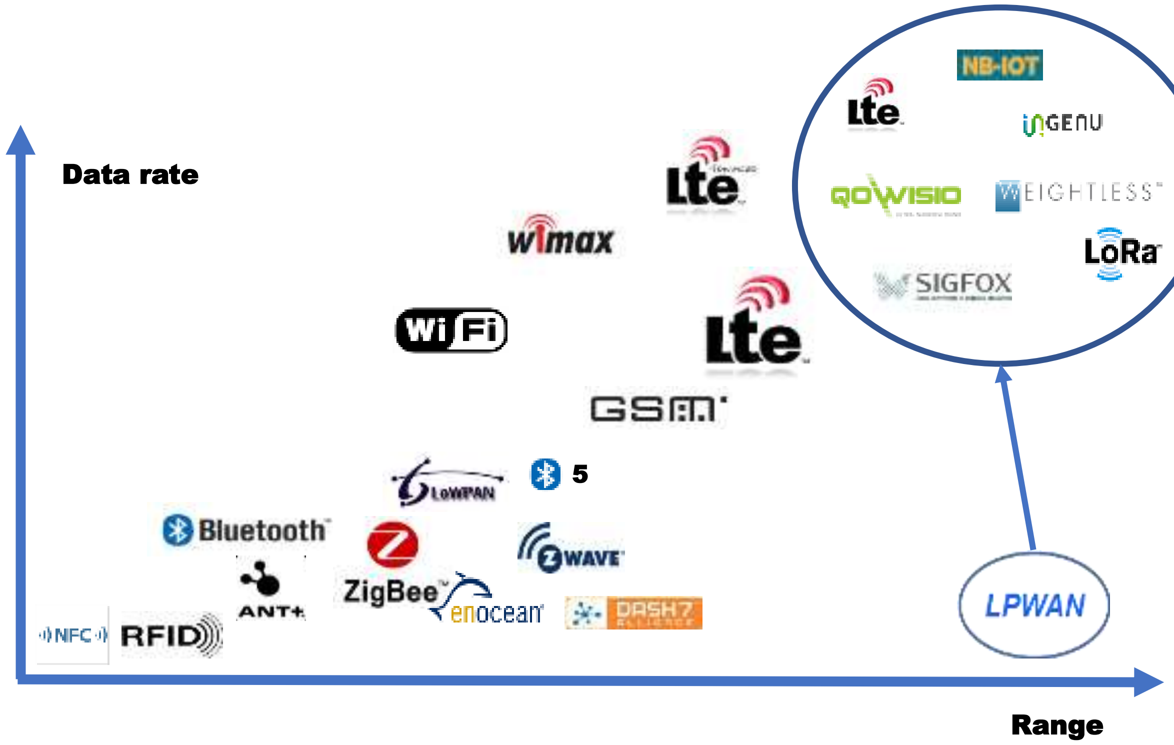

Fig. 6. Wireless technologies

Although a lot of technologies exist, not all are relevant or future-proof for smart buildings. Most of them are/were used, but some are more appropriate while others tend to disappear quickly in the future. Expensive and proprietary technologies cannot compete that much with cheap emerging technologies promoted by strong consortia.
The diversity of technologies is also a good point since the needs will not be the same for a smart home and a smart building. The most important characteristics are:

- Price
- Power consumption and power delivery (battery or energy harvesting)
- Indoor range
- Ease of deployment
- Durability

3.3. The link budget

3.3.1. Principles

The link budget is a method to compute all kind of gains and losses of a signal sent by a

transmitter, through the medium to the receiver. We will see that this method can give a theoretical estimation of the indoor range, this last point being important in the choice of the wireless technology in Smart Buildings.
The link budget is expressed as:

$$Received\ Power_{dB} = Transmitted\ Power_{dB} + Gains_{dB} - Losses_{dB}$$

The principle of a wireless communication is the following one: The transmitter sends a message through a signal with a certain power. Then the receiver receives a noisy signal with a certain power. To have a successful communication the received power of the signal must be higher than the receiver sensitivity. The sensitivity of a receiver is the ability to extract the transmitted message from the received signal.
This sensitivity depends on the quality of the receiver, in other terms its signal processing electronic, the bandwidth of the signal, the temperature, the antenna performance …
It is also important that the signal is above the noise floor. Indeed, it is the physical limit of sensitivity and any signal below the noise floor cannot be measured. It can be computed with the following mathematical expression:

$$P_{dBm} = -174 + 10\ log_{10}(BW)$$

This gives the following result for different bandwidths (table 1)

Table 1. Noise floor for different BW under standard conditions

Bandwidth	Noise floor
1 MHz	-114 dBm
125 kHz	-123 dBm
200 Hz	-151 dBm

Table. 2 lists the sensitivity of some typical receivers for EnOcean, Bluetooth Low Energy, Z-Wave, Sigfox and Lora.

Table 2. Typical receiver sensitivity

Sensitivity	Receiver
-96 dBm	STM300 ENOCEAN ASK
-97 dBm	TI CC2640R2
-98 dBm	STM300 ENOCEAN GFSK
-103 dBm	TI CC2640R2 @125 kbps / Z-Wave @9.6 kbps
-137 dBm	RN2483 LoRa@0.25 kbps / ATIM Sigfox

The life of a signal from the transmitter to the receiver is presented in Fig. 7.

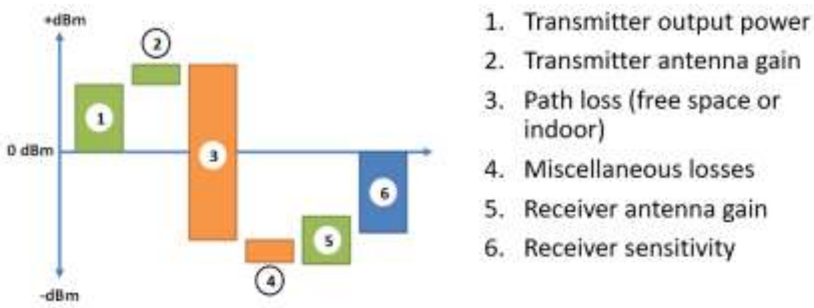

Fig. 7. Gains and losses of a signal transmitted

This is a graphical way to present the link budget, with the gains in green and the losses in orange. It is obvious that the main losses are due to the path loss. The distance and the obstacles, such as walls and floors, increase this path loss.

3.3.2. Maximum link budget

The maximum link budget can be calculated as:

Maximum link budget = Max Output Power – Receiver sensitivity

We computed some of the typical maximum link budget for the different wireless technologies in the table below. The path loss must be lower than this value.

Table 3. Typical maximum link budgets

Standard	Max link budget
Z-Wave (9,6 kbps)	107 dBm
Bluetooth (125 kbps)	108 dBm
EnOcean	103 dBm
LoRa (0.25 kbps)	151 dBm
Sigfox	151 dBm

A way to increase the maximum link budget would be to increase the transmitted power itself. Typical values can be seen in table 4.

Table 4. Indicative power values

Transmitted power	
Z-Wave	4 dBm
Bluetooth	5 dBm
EnOcean	7 dBm
LoRa & Sigfox	14 dBm
Wi-Fi	16 dBm

The negative side of this method is that it leads to higher power consumption and problems with the European Radio Equipment Directive.

Fig. 8. Frequency usage of different technologies

3.3.3. Path loss

When the perfect conditions are available, in other words in straight line, without obstacle or perturbation, the best ranges of communication can be reached. That is what we call the free space. Any signal transmitted in the free space is attenuated. It is known as the free space loss and can be computed with the following expression:

$$FSL = 20 \log_{10}(d) + 20 \log_{10}(f) - 147.55 \text{ dB}$$

With

d: distance

f: frequency

Some values are given in table 5 below some values of this free space loss for different distances and frequencies.

Table 5. Attenuation of the signal according to the distance and the frequency

Distance (m)	Frequency (MHz)	Attenuation (dB)
10	2400	60
100	2400	80
1000	2400	100
10000	868	111

In practice, these perfect conditions are not met. The attenuation can be much higher, especially in a buildings. The International Telecommunication Union (ITU) developed an indoor propagation model so the theoretical value of the indoor path loss can be computed:

$$IPL = N \log 10(d) + Pf(n) + 20 \log 10(f) - 147.55$$

with

N: distance power loss coefficient;

n: number of floors;

Pf(n): Floor loss penetration factor

The factors and coefficients depends on the building type: a house, an apartment block, an office, a commercial building …

The computed values for some specific cases can be found in table 6. E.g. BLE 5.0 would be attenuated by 100 dBm 100 meters around in a one floor residential building. It is less than the 108 dBm presented in the maximum link budget presented in the figure 6 which means the BLE 5.0 would be enough for the case. Now in an office with two floors, the highest distance to stay under the maximum link budget, still for the BLE 5.0, would be 20 meters. The BLE is for this not the best choice.
However, if we look at the LPWAN technologies (working at 868 MHz), such as LoRa and Sigfox, it can be seen that the maximum link budget is not reached in the case of the two floors office and 200m around.

Table 6. Free space and indoor path loss for different cases

Distance	Frequency	Free space Attenuation	Residential, one floor	Office, two floors
10 m	2.4 GHz	60 dBm	72 dBm	89 dBm
20 m	2.4 GHz	66 dBm	80 dBm	98 dBm
40 m	2.4 GHz	72 dBm	89 dBm	107 dBm
100 m	2.4 GHz	100 dBm	100 dBm	119 dBm
100 m	868 MHz	71 dBm	-	110 dBm
200 m	868 MHz	77 dBm	-	119 dBm

4. Wireless technologies

In this section, we will present the main characteristics of each wireless technology in the Smart Building use case.

4.1. LoRa

LoRa stands for Long Range modulation. This is a part of the emerging LPWAN (Low Power Wide Area Network) working on the ISM frequency 868 MHz and originally developed by Semtech. It is now promoted by the LoRa Alliance. LoRaWAN is used for high capacity and long-range star network. That MAC protocol is standardized by the LoRa Alliance.
This wireless technology has a low data rate (0.3 to 22 kbps) but has a high range estimated to more than ten kilometers in optimal conditions.
As it uses the entire channel bandwidth, it is less sensitive to noise than the other technologies using the frequency shift keying.
About the power consumption, the devices can last several months to several years since they only send some messages per day.
The network needs the Lora Gateway which is multi-channel, multi-modem, transceivers and can demodulate on multiple channel to get all the messages from the different devices.
This is a new technology which is growing really fast thanks to its ecosystem.

Table 7. Characteristics of LoRa

Cost	Intermediate, but should decrease rapidly (<12$ for SoC)
Power consumption	Several months to several years on battery (msg / day)
Indoor range	Best solution, several hundred meters, even with 5+ floors
Ease of deployment	Best solution for large buildings, no infrastructure except a base station
Durability	New technology, but very fast growing ecosystem. However, currently relies on one silicon vendor only

4.2. Wi-Fi

The Wi-Fi is a standard 802.11 used today. It works at the ISM frequencies 2.4 and 5 GHz. The Wi-Fi is a wireless technology well known today. It is protocol based on the standard 802.11 and working at the ISM frequency 2.4 and 5 GHz. This is also a certification given by the Wireless Ethernet Compatibility Alliance (or Wi-Fi Alliance) which verifies the specifications and interoperability of the devices in accordance with the 802.11 norm.
Indoor, the range of the Wi-Fi is about 40 meters. It keeps improving since we are theoretically above the Gbps with the 802.11ac. The main disadvantage of the technology is that it has a high power consumption. Any device using the Wi-Fi must be plugged.
The Wi-Fi is a really mature technology and has now a large ecosystem which makes this technology reliable with affordable equipment.

Table 8. Characteristics of Wi-Fi

Cost	Very cheap (< 2$ for a SoC)
Power consumption	Only days on battery, needs external power
Indoor range	~ 40 meters indoor
Ease of deployment	Depends on whether a local wlan infrastructure may be used
Durability	Mature technology and large ecosystem

4.3. BLE 5.X

The BLE (for Bluetooth Low Energy) or Bluetooth Smart is a wireless personal area network working at the ISF frequency 2.4 GHz. It was originally developed by Nokia. It is now designed, promoted and marketed by the Bluetooth Special Interest Group which is a strong ecosystem. The previous version BLE 4.X was already featuring a 1Mpbs rate, a range of 10 meters and a low power consumption which are nice characteristics for IoT and connected objects.
A new version emerged recently: The BLE 5.X. It extends the features of the BLE 4.X and is totally compatible with the old devices which were already implementing the BLE.
The bandwidth doubled (2 Mbps) and the time to transmit data reduced, while the ranges is 4 times the range of BLE 4.2 (depending on the strength of the signal).
This is a strong improvement for Smart Houses and Smart Buildings since it can provide a full coverage of an entire home in order to create home automation and security solutions.

Table 9. Characteristics of BLE 5.X

Cost	Very cheap (< 2$ for SoC)
Power consumption	Several months to years on battery or energy harvesting
Indoor range	~ 40 meters indoor
Ease of deployment	Ok for smaller & residential buildings otherwise needs complementary infrastructure
Durability	Mature technology and very large ecosystem (mobile), but new for the building

4.4. EnOcean

The EnOcean is a radio frequency technology originally developed by an offspring of Siemens, now by the company having the same name and promoted by the EnOcean Alliance. It works at the ISM frequency 868 MHz. The range indoor is about 40 meters.
This is a proprietary technology with a growing ecosystem but already with a wide variety of equipment. The principal advantages of EnOcean devices are a low energy consumption since they use photovoltaic cells, piezoelectricity, thermoelectric effect and they have a strong focus on inter-operability. It can last from several months to several years.
This technology is simple to use for smaller and residential buildings but is quite expensive

with a System on Chip for about 20€.

Table 10. Characteristics of EnOcean

Cost	Quite expensive (<25$ for a SoC)
Power consumption	Several months to years on battery or energy harvesting
Indoor range	~ 40 meters indoor
Ease of deployment	Very simple for smaller & residential buildings. Use repeaters and gateways for larger buildings
Durability	Growing ecosystem, a lot of equipments already. BLE 5 is a serious challenger. One silicon vendor only.

4.5. Z-Wave

The Z-Wave is a radio frequency technology which is also working at the ISM 868 MHz in Europe. A Danish company Zen-Sys originally developed it. The range indoor is about 40 meters and the data rate from 9.6 to 100 kbps.

Since it is designed for home automation, it is a direct concurrent of EnOcean and BLE 5.X. At this time, Z-Wave has a well-established ecosystem and already a lot of equipment. It is simple for smaller and residential buildings and has the possibility to extend the network thanks to the mesh network. However, that kind of network can get quickly complex.

Opposite to his concurrent EnOcean, Z-Wave is cheaper but needs more power and only works on a battery, which means it can last several months only.

Table 11. Characteristics of Z-Wave

Cost	Intermediate (<10$ for a SoC)
Power consumption	Several months on battery (mesh networks)
Indoor range	~ 40 meters indoor
Ease of deployment	Simple for smaller & residential buildings. Complexity of mesh networks
Durability	Well established ecosystem, a lot of equipments already, but BLE 5 and EnOcean are serious challengers

4.6. Example: low-power wireless communication system for self-sufficiency IoT objects developed at University of Lille1

4.6.1. Introduction

To give access to buildings or to basically control and monitor them for heating and lighting for instance, one can use dedicated wired networks like KNX, DALI and at a higher level, BACnet or Ethernet backbones. That can easily be done by directly using Industrial PLCs including WEB services. Easily done for buildings under construction and absolutely necessary to achieve performance requirements, one can compare this in renovation to what happened with the democratisation of Internet. Without needing construction work, WiFi brings great comfort compared to the deployment of a copper wired Ethernet network. On the other hand, wireless communication is less secure and suffers from lower bandwidth.

Mobile applications and services become very common and useful to control and monitor Smart Buildings. Since Bluetooth is a wireless technology protocol available on every smartphone and tablet it naturally became a standard in indoor domotics communication. Dedicated to exchange data with Smart objects over short distances one can imagine to control objects using Bluetooth in a room, an individual house or an apartment but it becomes more complicated to control a building using Bluetooth. On the other hand, as well as Wi-Fi, Bluetooth is not a low power consumption technology. While it is true that Bluetooth Low Energy (BLE) performs better in power consumption and range than standard Bluetooth, its interest remains limited due to a lower bandwidth. Other solutions like LoRa and SIGFOX offer wireless communication on a higher range than Bluetooth (> 10km) but suffer from a very low bandwidth. These technologies are mostly dedicated for remote reading of consumption and for wireless basic control of small objects of the Internet of Things (IoT) like traffic lights for instance.

Star networks as shown fig. 9 are one of the most common wireless network topologies. Communication is organized around a central acces point (or router) illustrated in red in fig. 9 left. Cluster tree networks (fig. 9 center) and mesh networks (fig. 9 right) can in some occasion been proposed as a star network extension.

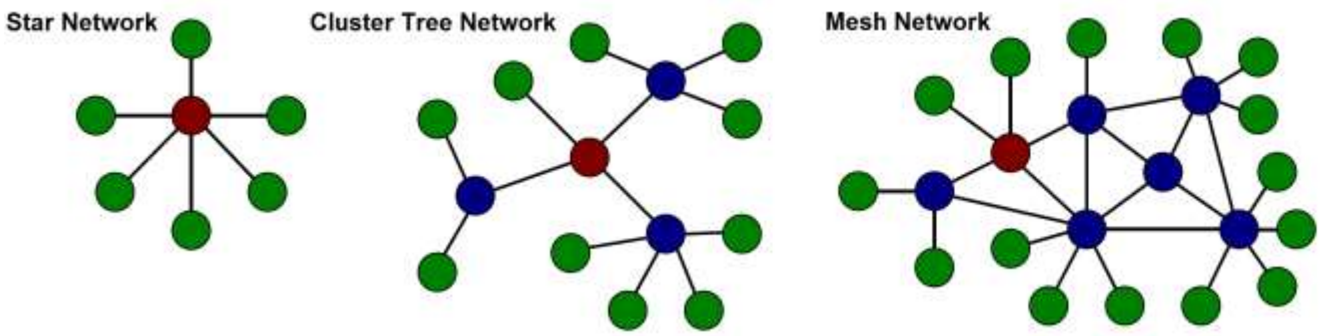

Fig. 9. Common wireless networks topologies

At last, the price of a node equipment or of an IoT device has to be as low as possible. Most of time products cost less than 10€.

4.6.2. Specifications of the low-power wireless communication system

As pointed out above, low-power consumption, energy self-sufficiency, range, bandwidth and security are important aspects of an IoT object. In that way University of Lille1 has developed an open IoT object environment based on common prototyping boards and a separate wireless transceiver.

The specifications of this IoT wireless system are to:

- Develop a low power consumption client-server system,

- Make remote control of digital and analog outputs,
- Make remote reading of digital and analog inputs,
- Allow a range extension of the network based on a cluster tree topology (see fig. 9),
- Develop a Human Machine Interface (HMI) connected to a data base.

To achieve this it is asked to:

- Use low-power and power down able nRF24L01 2.4GHz wireless data communication transceivers,
- Use low cost prototyping boards like the ARDUINO and the Raspberry PI,
- Evaluate boards power consumption,
- Perform deep sleep of microcontrollers when unused or as much as possible,
- Establish the link with a remote reading database.

4.6.3. Communication modules

Several communication modules fulfil the requirements for the proposed system.

Wi-Fi

The ESP8266 illustrated figure 10 is a serial transceiver Module based on IEEE802.11/b/g/n Wi-Fi standard[4]. This less than 2€ PCB uses an Espressif ESP8266 chip [9]. The chip itself implements a full TCP/IP protocol stack and has a large computational power on-board. That means that you can use this board as a simple Wi-Fi communication management board for an ARDUINO or a Raspberry PI. One can also use it to offload a main processor for some tasks. The ESP8266 can be used stand-alone to exploit its full power by implementing the logic inside the board itself instead of putting it in an ARDUINO for instance. Thus you can manage sensors and elaborate autonomously their signals and measurements. Hosting simple applications on-board can let it make a very compact IoT solution as well as a low cost powerful WEB server.

Enjoying all the benefits of Wi-Fi the ESP8266 gets also some of its shortcomings since power consumption is dramatically high (60 to 300mA). Impossible then to run it on AA/AAA alcalin or lithium-ion batteries since energy self-sufficiency would ridiculously fall down to just one day at the highest.

Nevertheless provides the ESP8266 an interesting and efficient less than 80µA power down mode combined to a lower than 2ms wakeup delay. However it should be noted that in power down mode it becomes impossible to communicate with the chip.

[4] http://espressif.com/en/products/hardware/esp8266ex/overview

Fig. 10. ESP01 transceiver based on the Espressif ESP8266 Wi-Fi chip (25x14mm)

Bluetooth / BLE 4.0 / Bluetooth 5

Bluetooth[5], originally introduced by Nokia in 2006, is one of the most used short range (<100m) 2.4GHz wireless protocols in IoT specifications, especially with the introduction of the Bluetooth Low Energy, an extension also known as iBeacon by Apple users. Both Bluetooth and BLE comply with the IEEE802.15.1 standard and the most important benefit of BLE protocol is its low peak current consumption lower than 15 mA due to the emission of small data packets as compared to the classic Bluetooth 3.0, which helps the making of full battery powered boards. The working time when powered by a 1000 mAh battery can then be longer than two years in some occasion (deep sleep current of 11µA) but is dramatically reduced to just a few hours in case of continuous data transmission.

Another interesting feature of Bluetooth for Smart Building mobile HMI specifications is that this protocol is directly implemented on many smartphones and tablets. This facilitates the setup of a mesh network of Bluetooth devices with lower latency and higher range but lower data rate (1 vs 3 Mbps). Last but not the least arrives Bluetooth 5[6] that will quadruple BLE 4.0's range but at only 128 kbps data rate and multiply by eight the messages length.

Bluetooth 4.0 Modules like the HM-11 illustrated on figure 11 cost less than 4€ and can easily be interfaced with micro-controllers.

Fig. 11. Seed Studio Bluetooth 4.0 HM-11 BLE Module (19x14mm)

[5] https://www.bluetooth.com
[6] https://www.bluetooth.com/specifications/bluetooth-core-specification/bluetooth5

ZigBee

ZigBee is a suite of communication protocols based on IEEE 802.15.4 standard used to create low-power WPANs. Baud rate is low (20kbps in the 868MHz band, 240kbps in the 2.4GHz band). If ATMEL ZigBee AT03663 chips[7] have a typical power consumption in transmission of around 3 to 15mA, it falls down to 2µA is power save mode and is less than 1µA is power down mode. Devices working time when powered by a 1,000mAh battery can then be longer than two years. Note that as for all low power in transmission devices, distances between two ZigBee chips are limited, here to 10 to 100m. That said a very interesting specification of ZigBee is that devices can transmit data over long distances by passing data through a mesh network (see fig. 9) of intermediate devices to reach more distant ones.

ZigBee is typically used in secure networking since it is supporting 128-bit encryption: home automation, healthcare, industrial control applications with short range and low bitrate.

Fig. 12. Zigbee Module (28 x 22 mm)

Nordic 2.4 GHz RF-transceiver

The Nordic nRF24L01[8] is a highly integrated, ultra-low power 2Mbps, 2.4GHz RF band transceiver developed for wireless personal area networks (WPAN). With peak transmission and reception data currents lower than 14mA, a sub µA power down mode and an advanced power management, the nRF24L01 enables months to years of battery lifetime when running on 1,000mAh coin cells or AA/AAA batteries. The Enhanced ShockBurst™ hardware protocol accelerator additionally offloads time critical protocol functions from the application microcontroller enabling the implementation of advanced and robust wireless connectivity with low cost microcontrollers. nRF24L01 printed circuit boards (PCB) with built-in antenna and voltage regulator (fig. 13) are very small and cost less than 1€ making it also a good value for money IoT specifications. At last, the outdoor short-range between two nRF24L01 devices

[7] http://www.atmel.com/Images/Atmel-42321-Power-Consumption-of-ZigBee-End-Device_ApplicationNote_AT03663.pdf
[8] http://www.nordicsemi.com/eng/Products/2.4GHz-RF

(15-60 meter or so) can be enhanced up to 600m by using an external 2.4GHz antenna (fig. 13 right) making it great to use in Smart Building applications.

As an actor of the Bluetooth standards specifications, Nordic's nRF24L01+ extension of the nRF24L01 is able to send and receive data over Bluetooth Low Energy 4.0 (BLE) when nRF52 series (nRF52832 and now nRF52840) comply totally with the Bluetooth 5 standard.

Fig. 13. nRF24L01 board with built-in (left) and external (right) 2.4GHz antennas

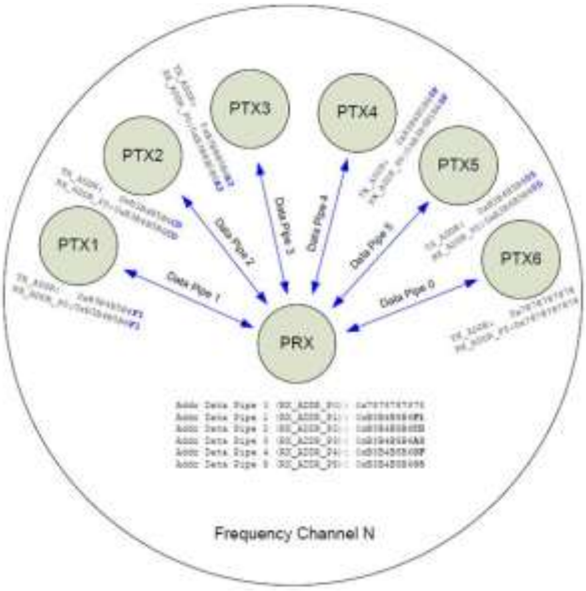

Fig. 14. nRF24L01 basic topology

The Nordic nRF24L01 transceiver common topology is a star network (fig. 9). The defining Reception (RX) / Transmission (TX) capability (multiceiver) is having up to 6 wireless communication channels (pipes) simultaneously opened in reception mode at start-up inside a single 2.4GHZ frequency channel. This takes the form of a primary receiver hub (PRX) and thus up to six primary transmitter nodes (PTX1 to PTX6). That means that six reading data pipes are initially opened in the PRX primary receiver. Each PTX node has to link to one of these 6 available pipes and can after that use it both in transmitting and receiving modes. The nRF24L01 communication protocol specifies that each device can be used for transmission only, reception only or both transmission and reception. Two modes of communication request are also available per channel, a "one to one" (point to point) and a "one to all" (broadcast) one.

The nRF24L01 can handle a maximum payload of 32 bytes (256 bits) in a single data frame. That means we can refresh up to 256 Boolean variables or 16 16 bits of resolution analog values in just one data frame.

4.6.4. Basic topology of self-sufficient IoT system

Figure 15 shows how to extend a nRF24L01 transceivers network. Example shows a client / server architecture where each end device (1xRaspberry PI, 3xARDUINO) is connected to a distinct nRF24L01 transceiver.

The Raspberry PI plays the role of the PRX hub and is here seen as client of three sensors data servers (PTX) hosted by ARDUINO 1, 2 and 3.

ARDUINO 1 and 2 are in sight of the PRX when ARDUINO 3 can't be reached being too far from it. ARDUINO 2 is then used as a relay between the PRX and this PTX. Five channels are used to organize the communication between the devices.

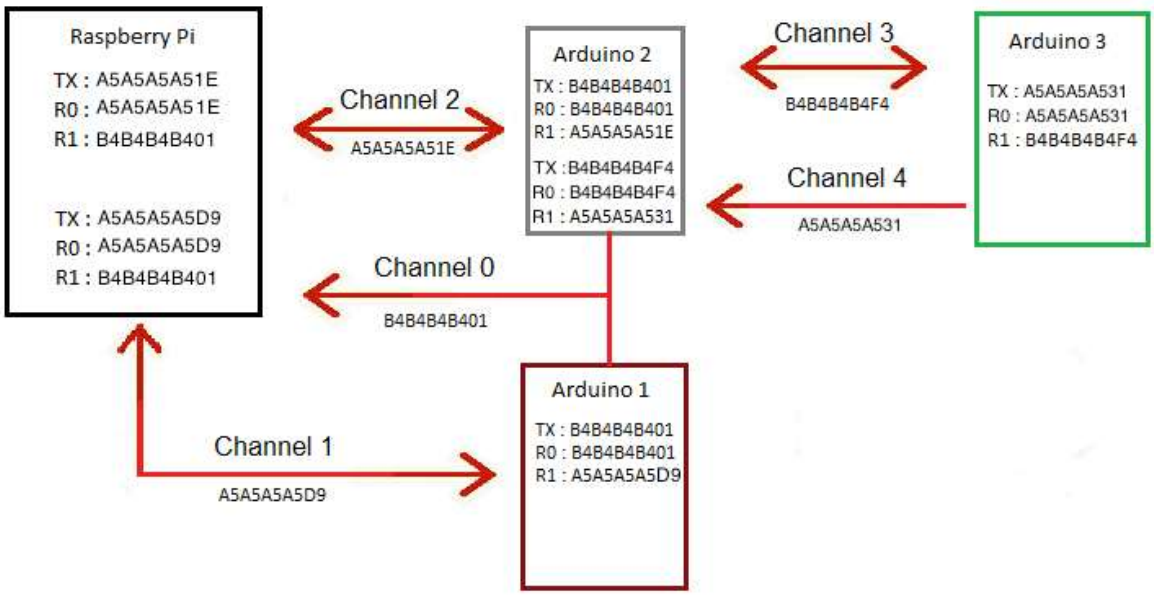

Fig. 15. Basic topology

As mentioned before the power consumption and at last the self-sufficiency of a wireless network is directly in link with the range, the transmission load, the kind of communication way (Wi-Fi, Bluetooth…) and the device role (client / server).

It seems obvious that a simplex (unidirectional) communication uses far less energy than a half/full duplex one where devices can be requested at any moment. That said much end devices need both to send and receive information. An internal real time clock can then be helpful to synchronize devices by allowing RX/TX communication during short periods of time.

Table 12 shows some results when comparing three communication modes established between the Raspberry PI and ARDUINO 1, 2 and 3 (see fig. 15). These communication modes that allow or not deep sleep mode of controller and nRF24L01 transceiver are:

- A simplex communication, device is transmitter only,
- A half-duplex asynchronous communication (RX then TX),
- A half-duplex synchronous communication period (RX and TX) during 1 time slot and then 4 times in deep sleep mode (20% of bandwidth use).

Table 12. nRF24L01 communication modes comparison

	Case 1: Simplex	Case 2: Asynchronous half-duplex	Case 3: Synchronous half-duplex
Specifications	* Raspberry in RX mode * ARDUINOs in TX mode sending 1 data frame each hour	* Raspberry in TX mode * ARDUINOs constantly waiting in RX mode	* Raspberry in TX mode. Communication at given times * ARDUINOs waiting in RX mode at the given times
Sleep mode available (Y/N)	Y	N	Y
Benefits	* Adapted for remote reading * High efficiency in energy saving	* Communication possible at any time	* Adapted for remote reading and low cycle time process control * Good efficiency in energy saving
Limitation	* Remote reading driven by the data sender	* No energy saving possible * Highest power consumption	* Not for real time process

Table 13. Energy consumption

Mode veille			**Transmission**	**Réception**
Power down	*Standby-1*	*Standby-2*	*PA_MAX (0dBm - 2Mbps)*	
900 nA	22 uA	320 uA	11.3 mA	12.3 mA

4.7. Summary

When retrofitting existing buildings to make them “smart”, deployment and maintenance costs may be strong barrier to adoption. In this context, zero wire devices (wireless communication + energy harvesting) represent a powerful solution to overcome these barriers.

We presented several wireless technologies that could be a part of the technological mix needed to achieve zero wire devices. Two of them are for us the most promising technologies: BLE 5 and LoRa.

They are new to the building sector but also the most promising in two different sub-markets: the residential/small buildings in one hand and the large buildings in the other hand.

5. Control & HMI

5.1. Home Automation Platforms

In the research done by Guo et al. (Guo 2017[9]) several HA components were combined and tested for the purpose of a voice controlled home system. The following paragraphs describe the different configurations. In this respect, it must be stated the development and integration of Home Automation Platforms goes rapidly. Google, Amazon, Apple offer complete HAP embedded in their portfolio. In this part, several technologies and combination of technologies are discussed.

Concept 1: CastleOS + Kinect + FIBARO

This is a combination setup of CastleOS Hub, Kinect and all the necessary FIBARO components. Based on a large amount of market research the concept 1 shows the significant possibility of combining different products. In this concept, CastleOS with powerful functionality and unlimited "smart capabilities" determines why we use it as a center controller.

One of the most notable factors is the outstanding voice control, the main feature compared to other voice control system is the ability to place microphone arrays in a room and pick up a command spoken out loud anywhere, anytime. No app needs to be open and no button needs to be pressed.

However, compared to CastleOS, the reason why we use Fibaro smart devices instead of its center control is that the functionality of Fibaro is powerful enough to meet all the requirements but the voice control is quite weak. The Lily which they have in beta is a voice control via a mobile app. You will need to activate the app and speak into a device to give your command. It is quite different from CastleOS. On the other hand, CastleOS can support ZigBee, Z-wave. Wi-Fi and Bluetooth to communicate with different smart devices but Fibaro only support Z-wave. Therefore, in some ways it limits the number of smart device. Meanwhile, Starlock is the perfect choice of door lock, which can communicate over the Z-Wave protocol. The only drawback is the high price.

By consulting the technician of CastleOS, it is concluded that using Fibaro devices and sensors with CastleOS is not a problem. Fibaro devices actually communicate over the Z-Wave protocol, which CastleOS also communicates with. In Z-Wave, each device has a "profile" that defines its features and abilities. Adding support for any particular device is simply a matter of us loading the proper device profile into CastleOS. So not only do they currently support many Fibaro devices, they also can easily add support for any device that is not currently defined in CastleOS just by adding its profile.

Concept 2: Homeseer + Evolve + Aeon

This is a combination setup of HomeSeer controller S6 and all the necessary Z-Wave components.

[9] Guo, C, et al. ; *HZ Project "Platform Choice for a Voice & Gesture Control System"* . Vlissingen 2017

This set-up is mainly determined by the controller—HomeSeer S6. It is a home automation controller combines the reliability and simplicity of a panel-type controller with the power and flexibility of a software-based controller. No other hardware controller offers voice recognition, complete telephone integration, text to speech processing, email functionality and full SSL protected remote access. The system is managed using any web browser. This allows for easy configuration on or off site. Remote access to the unit offers the ability to remotely manage the unit without making a trip to the site. Easily add/change schedules, or troubleshoot issues.

Another important issue is that Homeseer can support Insteon, UPB, Wi-Fi, X-10 and Z-Wave. Since X-10, Insteon and UPB can support power-line based, and Wi-Fi, Z-Wave can support wireless protocols. So it can bridge the gap between powerline-based and wireless protocols, it uses both. If the home is outfitted with an older X-10 system, go with this set-up. It will allow you to go wireless; and it boast many compatible devices of Z-Wave, it does have a good selection of products.

Concept 3: Voicepod + Belkin + Nest+ Aeon

This is a combination setup of VoicePod tabletop device and all the necessary ZigBee components.

The ZigBee-enabled VoicePod is a self-contained controller with a speaker-independent speech-recognition engine built in. There is a good feature that the VoicePod comes with a "Basic" menu of speech-recognition command sets such as "Good morning," "Good night," "Watch TV," and "What is the temperature?" VoicePod offers voice response and prompting through the onboard speaker. For example, if the user says, "Watch TV," the unit will reply, "What channel?"

When more than one VoicePod hears the wake-up phrase—"hello Voicepod?" the devices automatically communicate with each other over ZigBee to prevent more than one from answering. Only the one that hears the user the best answers. The patented technology solves a critical issue that any serious system allowing hands-free wake-up will face.

Concept Choice

After determining 3 concepts the researchers (Guo 2017), chose one of the three concepts as the final solution of this project. The group uses the requirements list to make a comparison of these 3 concepts (Appendix V). The concept which can satisfy all the requirements would be the best choice.

Conclusion

As stated in (Guo 2017) based on the check on the List of Requirements and Specfications, Concept1 (CastleOS) can satisfy all the requirements while the other two cannot. Concept2 (HomeSeer S6), it is a complicated piece of software, and most of the capabilities are via third-party plugins that are not supported by HomeSeer itself. In addition, the voice control it offers is rudimentary in comparison, and will always stay that way. Concept3 (Voicepod), is more oriented to the American Market. The price is higher than the other two.

5.2. Human Machine Interaction

5.2.1. Interaction types

Human machine interaction (HMI) and human computer interaction (HCI) are mainly understood as employing graphical user interfaces (GUI), presenting the machine status and information in a transparent and ergonomic way for the user. Although control by pushing buttons and sliders on screens and visual feedback through a GUI is important and wide spread, other types of interaction are emerging. Industrial applications in Industry 4.0 are further developing to human machine cooperation (HMC), where the machine (robot) assists the user in his tasks. Types of control and interaction can be divided in:

- Hardware interfaces (real dashboards, knobs, cockpit)
- Command line interfaces
- GUI controlled by mouse, keyboard or touchscreen (visual feedback)
- Touch user interface (tactile feedback, f.i. Braille)
- Conversational interfaces (emulates natural conversation, chatbots, voice commands)
- Conversational interface agents (personification of machine by animation or robot)
- Gesture interfacing (gloves, stylus, acceleration sensors)
- Motion tracking
- Voice interfacing (control and feedback by voice)
- Augmented reality (addition of information on head up display, e.g. Google Glass)
- Virtual reality

5.2.2. HMI in smart buildings

Technology has become ubiquitous and that affects the way in which people interrelate with it. Trends in mobile devices and gaming technology have increased the acceptance of new interfaces, like touchscreens and game controllers. Mobile apps are also a way of managing a smart home. However, a lot of progress is made in other fields. Controlling a smart home can have huge benefits of hands free solutions. The number of interaction types are numerous, but for smart home environments, touchscreens, voice and gesture control are the most important technologies.

5.2.3. Example: Voice control system bases on HAP by the HZ University of Applied Sciences and Impuls Zeeland

Requirements

A cooperation between Amels Holland and Impuls Zeeland, “De drijvende huiskamer” is looking for ways to control several systems in a house or yacht using voice control[10]. The focus is on the door control and the cameras/intercom integrated into one system that can be

[10] The testing room 37A in Dok41 is provided by the client Amels Company, in which a series of installation and testing were conducted by the group.

controlled by voice. The first requirements the client gave for this system are:

- The front door lock can be unlocked using finger pattern recognition;
- The front door lock can be unlocked using a keypad;
- The front door lock can be unlocked using a keycard;
- The front door can be unlocked from an IPad;
- There is a doorbell to notify the inhabitant that someone is at the door;
- The inhabitant can see a video stream from a camera at the front door on an IPad;
- The inhabitant can talk to a person at the door using an IPad;
- The front door can be opened by the inhabitant by voice control;

Earlier research has been done and the basic setup has been chosen, a combination of Fibaro and CastleOS. Combining the two systems should result in a system that can be easily setup and expended (Fibaro) and voice controlled (CastleOS). On this system, entrance control, intercom and cctv is installed. The focus is on the door control and the cameras/intercom integrated into one system that can be controlled by voice.

System components

In this concept, CastleOS is chosen as the central hub because it offers the most powerful and flexible voice control available, "out of the box". It automatically recognizes thousands of natural-language commands and automatically recognizes new smart devices by name. In this system Kinect is used to receive voice commands, which are processed by a PC or CastleOS hub. It is worth mentioning that Kinect can be used to realize gesture control. At this point gesture control is not supported by the CastleOS software but it is being worked on by the developers.

CastleOS supports a connection with several home automation devices using: ZigBee, Z-wave, Wi-Fi and Bluetooth. In the concept the Fibaro Z-wave protocol is chosen to communicate to actuators and sensors which Fibaro products. Fibaro also has its own central control product called “Home-Center 2”. The reason this product is not used as a hub is because their voice control, called Lily, is inadequate for the project. Currently Lily is only available as a mobile app. The users need to activate the app and speak into a device to give voice command. With CastleOS you can place microphone arrays in a room and then pick up a commands spoken out loud anywhere, anytime. No app needs to be open and no button needs to be pressed.

Kinect is a line of motion sensing input device by Microsoft for Xbox 360 and Xbox One video game consoles and Windows PCs. Motion detection is the process of detecting a change in the surroundings relative to an object. In combination with CastleOS the Kinect gives your complete control over your home with an accurate and sophisticated whole-house natural language voice recognition system that monitors your home and listens for command prompts 24/7 without relaying interference from loud music, movies, TV, and other noises. There is no limit to the amount of Kinect devices that can be connected to your home system, but additional Kinects increase the standard 35-foot transmission range.

The Kinect product itself is a horizontal bar connected to a small base with a motorized pivot and is designed to be positioned lengthwise above or below the video display. The device features an "RGB camera, depth sensor and multi-array microphone running proprietary software”, which provide full-body 3D motion capture, facial recognition and voice recognition capability. The depth sensor consists of an infrared laser projector combined with a monochrome CMOS sensor, which captures video data in 3D under any ambient light conditions. The sensing range of the depth sensor is adjustable, and Kinect software is capable of automatically calibrating the sensor based on gameplay and the player's physical environment, accommodating for the presence of furniture or other obstacles.

For allowing the user to see who is at the door and have closed circuit television (CCTV) inside of the room. The IP-camera chosen is the AXIS M3004-V. It comes with a fixed lens unit and provides a horizontal viewing angle of 80° with HDTV 720p, 1MP image resolution. The camera connects and is powered with through Ethernet. According to Chris Cicchitelli Founder and CEO of CastleOS it is not possible at this point to integrate the IP-Camera`s in the CastleOS system. This feature is coming late 2016/early 2017 and as soon as a beta version is available we can start using it. Until that time we will use a separate app for connecting to the cameras. Also the Kinect has a camera build-in, possibly this can be used for CCTV purposes as well. The Kinect's various sensors output video at a frame rate of ~9 Hz to 30 Hz depending on resolution. The default RGB video stream uses 8-bit VGA resolution (640 × 480 pixels) with a Bayer color filter, but the hardware is capable of resolutions up to 1280x1024 (at a lower frame rate) and other color formats such as UYVY. The monochrome depth sensing video stream is in VGA resolution (640 × 480 pixels) with 11-bit depth, which provides 2,048 levels of sensitivity. The Kinect can also stream the view from its Infrared laser camera directly.
Using the Kinect camera for CCTV is coming to the CastleOS in a future update (late 2016). It will use the same USB connection as the voice control.
To allow the user to open the front door remotely and get in using your fingerprint a lock from Art Guard Security is chosen. The specific model is the Starlock 8028. According to the information on the website this lock can be unlock using a keypad, a pin code, voice control, an IR-remote and a RFID card. By Z-Wave, the lock will be controlled using the CastleOS software.
Finally, the functionality to have a voice connection with the person at the door is needed. Due to the link with the system, a network based solution is necessary (Wi-Fi or Ethernet), viz IP-Intercom. At this point it will only be possible to use the intercom in a separate app from CastleOS but together with the update for the IP-camera`s it will become possible to use CastleOS in combination with Kinect as an intercom system.
For connecting all the devices that cannot connect to the Z-wave we will use a local area network (LAN). The IPad and the PC can connect to each other either through Wi-Fi or Ethernet. Both the intercom and the cameras are IP-devices which means they can also connect to them through a network connection (Ethernet or Wi-Fi). These specific models use an Ethernet connection. This can directly be plugged in to a router as long as this router support a speed of at least 100Mbps (N300 Gigabit Router).
The storage of the images of the cctv can be done in the camera (SD-card) or on a central storage.

Based on the result of previous research, the CastleOS is chosen as the controller. However it has been proved that CastleOS isn't capable of being the center controller of the system. HomeSeer is selected as the new controller, which meets all the needed requirements. To take the control of the peripherals, there are two main connection patterns. The network connection is set up to make HomeSeer and peripherals work in the same local network, developing the signal transmission between PC and IP devices (eg. Camera and intercom) to realize mobile interaction on iPad or iPhone. By connecting to the USB-bus the Kinect takes the charge of inputting voice signal then processed by HomeSeer to match with the existing voice library. The other significant connection is to set up the link between the PC and Z-Wave devices. The Z- Wave adapter plugged in USB-bus working for Z- Wave interface is responsible for receiving and sending the Z-Wave signal to turn the ordinary PC into a fully customizable Z-Wave controller.

The full system can be seen on fig. 16.

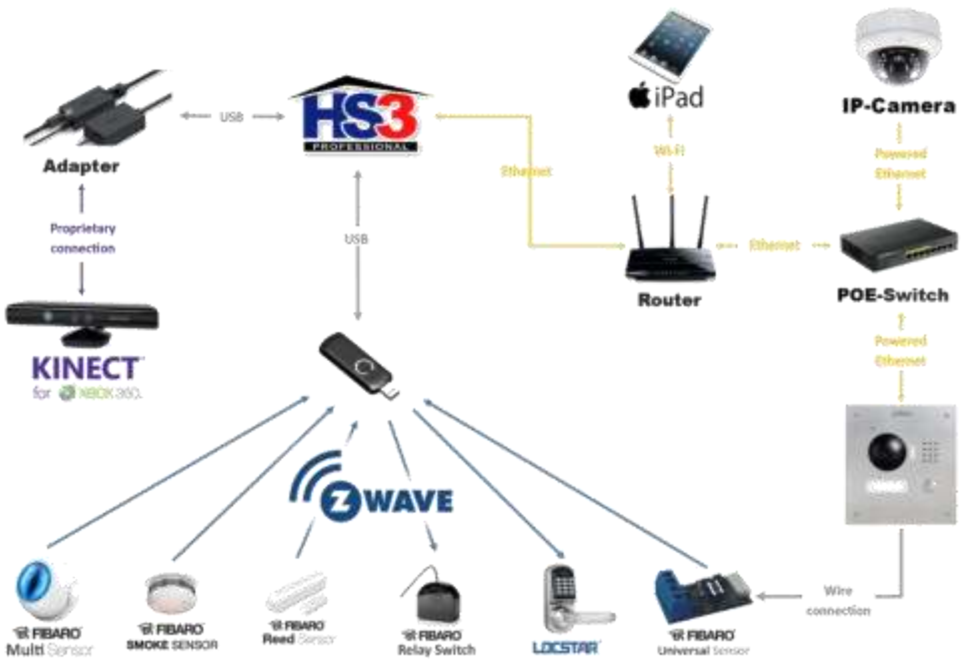

Fig. 16. System overview

Test results

Several scenarios where tested, combining the concerned systems and functions. Table 14 indicate the completed functions with the various ways they can be used.

Table 14. Functionalities

Completed Function	Method 1	Method 2	Method 3	Method 4	Method 5	Method 6	Method 7

Unlock the door	Voice control	iDMSS App	Web- page on PC	Emergency Key	Fingerprint	Pin Code	Key Card
Lock the door	Voice control	Physical Operation	-	-	-	-	-
Inter- conversation via Intercom	iOS Device	Android Device	Windows Device	-	-	-	-
Monitor the room	IP Camera	-	-	-	-	-	-
Monitor outside the door	IP Camera	Intercom Camera	-	-	-	-	-
Record images	IP Camera	Intercom Camera	-	-	-	-	-
Display recording	iOS Device	Software on PC	Android Device	Windows Device	-	-	-

The recognition accuracy of the software Homeseer is not very high, because only 30% commands can be correctly received by the software. The complexity of the commands and distance between the user and Kinect have a big impact on the results. The Homeseer software can support up to 232 devices so more devices can be added into the system. The sensitivity of the Kinect is very high so the environmental noise will affect the result.

5.3. Machine-learning

5.3.1. Introduction

Smart home or smart building design relies on the combination of several hard- and software new technologies. Concerning the software part, machine-learning algorithms play a pivotal role as they allow the system to make autonomous decisions. In this section, we review several machine-learning techniques that have been tested and implemented in smart buildings. Their benefits and limitations are discussed through several use cases that are in line with the objectives of the INCASE project.

Smart buildings is an application field, which aims at designing intelligent systems that can control and manage buildings with as little human supervision as possible. Any type of building is eligible for such technologies: homes, offices, factories, airports, schools and so on. Each building type may have its own specifications but the core idea is the same. In short, the building needs to be equipped with sensors
and actuators. Each such device must be connected to a central server through an appropriate network technology and protocol. Finally, software runs on the server. The software task is to collect all data coming from the sensors, analyze them and produce decisions as to when and how actuators should be triggered.
Concerning the software aspects of smart buildings, artificial intelligence algorithms are key components of the decision system. Among the vast artificial intelligence literature, machine learning has proved to solve complex decision making tasks with remarkable accuracy. Machine learning is a research field that attempts to reproduce learning principles from animal

psychology into programming code. In general, the machine is given a dataset containing input-decision pairs. The algorithm exploits these data to predict decisions when new inputs are given. In this report, we review state-of-the-art machine learning techniques that have been proposed and tested in the context of smart buildings. We start with a quick reminder on machine learning paradigms and recall several notions in this field. Since smart building systems usually require to solve several tasks, we review several use cases separately. The rest of this chapter is therefore organized with respect to each use case.

Smart factories and technical building management are two fundamental questions addressed as part of the INCASE project. Although some of these use cases are not always directly related to these questions the devices implemented may provide information allowing to address other tasks. For instance, INCASE is interested in power consumption monitoring but power consumption can be useful to detect abnormal behavior within the building. In addition, all intelligent systems are built using the same machine learning building blocks, therefore all the solutions discussed in this report can be transposed to INCASE related problems. For instance, we discuss human detection using imaging sensors. This technology can be used track the activity of staff members inside a factory and provide assistance to them. It can also be argued that visual understanding algorithms are key elements for this application. Such algorithms can be used as well to detect motions that could be used to trigger lights or production sub-systems.

5.3.2. Machine learning basics

Generally speaking, machine learning aims at producing algorithms that have a predictive power. One can reach that goal by exploiting data and optimizing an objective function that features the impact of prediction errors as well as prediction successes. As said in the introduction, the mathematical and algorithmic mechanisms that are employed in machine learning are inspired from learning principles in animal psychology. This means that the decisions of the systems are compared to the correct ones and that the algorithm updates itself to avoid reproducing incorrect decisions in the future.

The learned models allow solving multiple tasks that can give the feeling that the machine has its own reasoning capabilities. Actually, this is of course fictional. All the decisions produced by the machine are direct consequences of humanly programmed computation. In other words, machines do not make decisions on their own they just obey code lines.

In this section, we review machine-learning paradigms and recall important related notions. For more comprehensive presentations of machine learning, reference books[11] may be browsed.

5.3.3. Supervised learning

A supervised learning problem starts with a dataset. Each data in this set is a pair

$$(x(i), y(i))$$

[11] E.g.: C. Bishop. *Pattern Recognition and Machine Learning*. Springer, 2006 and K. P. Murphy. *Machine Learning, A Probabilistic Perspective*. MIT press, 2012.

for i from 1 to n. In this pair, $\mathbf{x}^{(i)}$ is called an example and $y^{(i)}$ is called an output (or decision). The algorithm must learn the functional relation f_0 between any example $\mathbf{x}$ and its outputs $y = f_0(\mathbf{x})$.

Example: Suppose a customer applies for a credit card in a bank. The bank has some personal information about the customer (salary, account balance, total debt, age, gender and so on). This set of information pieces is an example **x**. The corresponding output is binary (allow or deny the card)

Each piece of information inside an example is called a feature. The space where examples live is usually referred to as feature space. Most of the time, this space is a vector space and we can use linear algebra calculus. Sometimes examples contain categorical data like the customer gender in our example. However, categorical data can be embedded into a vector space. Consequently, we will make the assumption that any example **x** is a vector in R^p in the remainder of this document.

The integer p is the dimensionality of the examples while n is the number of examples. In modern machine learning, a famous bottleneck is termed big data. This means that n is very large and typically, the dataset cannot be loaded on a single computer memory. When p is large, one speaks of tall data.

Supervised learning is subdivided into two categories: classification and regression. Classification deals with categorical outputs like the accept or deny decision.

In this case, y live in a set C that is deprived of any mathematical structure. Regression deals with continuous outputs living in a vector space. For instance, if the bank wishes to determine the maximal mortgage that can be granted to the customer, then this becomes a regression task.

Since our goal is to determine function f_0, the solution space has an infinite dimensionality. Most of the time, people resort to parametric models, that is, candidate functions are in bijective correspondence with a parameter vector $\boldsymbol{\vartheta} \in \Theta$ and the space Θ has finite dimensionality. Even if this simplifies the problem, this latter is still ill posed in the sense that they are infinitely many functions f_ϑ such that

$$f_\vartheta\,(x^{(i)}) = y^{(i)},\ \forall i$$

This established fact implies that learning algorithms must resort to additional constraints to converge to a solution. Usually, the chosen parametric model will not allow the estimated function $\hat{f}$ to have chaotic variations. The machine learner has done a good job when a trade-off has been found between predictive function complexity and data fit. An excessive data fit is a situation called overfitting while an excessively simple decision function is a situation called underfitting.

5.3.4. Unsupervised learning

In the unsupervised learning paradigm, the learner is also given a dataset, but the dataset contains examples only. The outputs are missing. In the worst case, the number of classes into which examples must be sorted is not known either.

The only available information is proximity between examples. Indeed, if two examples are close in the feature space, the usual assumption is that they belong to the same class. When data points seem to aggregate around an attraction pole, they supposedly are member of the same class. This problem is also known as clustering.

Of course, unsupervised learning is doomed to perform poorly as compared to supervised learning. Unfortunately, acquiring labeled data (examples with outputs) is costly and difficult. Imagine someone wants to design a medical image processing software that can detect cancer signs. Only physicians have the appropriate skills to assign labels to such examples. Consequently, one needs to employ expensive staff for a boring repetitive task.

In many applicative context, only a subset of the dataset is labeled. This framework is known as semi-supervised learning. Another possibility is to give the learner a budget of $n^i < n$ examples for which he, or she, is given the correct output. In this setting, the learner queries the environment and therefore this paradigm is called active learning.

5.3.5. Reinforcement learning

The last paradigm that we evoke in this report is reinforcement learning[12]. This paradigm is dramatically different as compared to the previously mentioned ones. In this setting, the learner is not given a dataset, but it will be possible for him to build one of its own to some extent. Instead, the learner is given the possibility to try any input and obtain a reward in response to that input. The goal here is also to learn a function, but this function is meant to lead a commanded system to a desired state. The learned function is often referred to as the policy function. It should drive the system so that the desired state is achieved in the smallest number of moves possible. The motives behind reinforcement learning is connected to control theory. This paradigm is especially interesting in the smart building context for buildings con- tain several controllable systems that we wish to regulate automatically (heating, air-conditioned, lights, door access, etc.). Reinforcement learning is thus an interesting perspective as part of the INCASE project.

5.3.6. Anomaly detection

One of the most important goals of the INCASE project is to equip factories or technical buildings with many sensors and monitoring technologies. Suppose for simplicity that each sensor delivers a real 1D signal and that one records each signal for a given time span t_f. Suppose also we have m sensors. We can concatenate all these times series in a $m \times t_f$ matrix $\mathbf{X}^{(i)}$. If we collect several instances of such matrices, we can build an unlabeled dataset.

Although this is not the prime goal of these sensors, a general profile can be learned from this dataset. When we observe a new instance $\mathbf{X}$ that is significantly different from previously seen ones, then we can deduce that something potentially dangerous is happening. For instance, if power consumption is twice bigger than usual for several minutes then maybe a machine is malfunctioning and this could cause a mechanical accident or a fire outbreak.

[12] Richard S Sutton and Andrew G Barto. *Reinforcement learning: An introduction*, volume 1. MIT press Cambridge, 1998

An example[13] is a system where daily electrical power consumption only is processed. He extracts features from each time series (average consumption, peak demand, etc.). The feature vectors are then sorted with respect to day types (Monday, Tuesday, and so on). Afterwards, outlier data points are sought inside each subset feature by feature. A statistic is computed to compare the absolute difference between the maximal feature value and its mean value. The outlier identification is performed by comparing the statistic to a critical value designed for this test when data points are normally distributed. This test is known as generalized extreme studentized deviate (GESD)[14]. Other example can be found in the full report.

5.3.7. Activity recognition

The devices that can be installed in a factory or a technical building, as proposed in INCASE, can also be used for human activity recognition. Many kinds of activities can be tracked. As part of smart factories, specific tasks of workers can be identified to provide them with appropriate assistance. For instance, if the system is able to detect that the worker is trying to assemble two pieces together, then a pre-calculated torque can be applied to help him (or her) to tighten a fastening screw. A more common task is also human presence detection. Such information is important for security (production may be stopped if someone is inside a given area) and for quality engineering (presence of people may corrupt the quality of the production in clean rooms).

In this section, we provide a quick overview of the human detection use case. First, let us stress that most approaches are non statistical and learning free. They resort on deterministic electrical engineering solutions. For instance, a simple solution is to equip building users with an RFID chip. If RFID antennas are deployed in the building, user positions may be easily tracked. The drawback of this approach is that building meshing is costly and users have to accept carrying chips.

Most of the time, occupancy detection requires anyway the installation of specific sensors. Whether the final objective is energy saving (as in INCASE) or not, low consumption sensors are preferred. In this vein, passive infrared sensors are an interesting solution. Human bodies emit photons in the infrared domain while non-organic matter do generally not. In particular, hot objects (like heaters) emit infrared photons therefore, sensors should be placed accordingly to avoid false positives.

Other low cost presence sensors examples are pressure sensors to detect chair occupancy, temperature, humidity, CO_2 and acoustic sensors. A slightly more costly solution consists in deploying a network of low-resolution cameras. The cameras need to be low resolution and produce images at low frequency for both cost and power consumption reasons. The images also need to be processed and classified in an embedded computing system. Images are processed so that background is suppressed and occupants thus produce blobs in the images. For indoor cameras, background suppression is not a costly operation. Blobs are groups of

[13] John E Seem. Using intelligent data analysis to detect abnormal energy consumption in buildings. *Energy and buildings*, 39(1):52–58, 2007

[14] Bernard Rosner. Percentage points for a generalized esd many-outlier proce- dure. *Technometrics*, 25(2):165–172, 1983.

connected pixels with a significantly high average value.
Outside the smart building literature, human detection has also raised a lot of interest. In particular, human detection in images and videos is a vivid research topic[15]. The major problem with the approaches presented in this community is that they rely on high-resolution cameras whose specifications do not meet our energy saving requirements.
In the computer vision community, deep learning algorithms have proved to obtain remarkable level of accuracy in scene understanding tasks. In this family of machine learning algorithms, popular models for video processing are recurrent neural networks (RNN) and long-short term machines networks (LSTM). These models are adapted for processing time sequences. Roughly speaking, they are neural networks implemented in a recursive fashion meaning that the output of the network at time t is the image of a linear combination of recent output history through a non-linearity (which is usually a sigmoid function). The weights involved in the linear combination encode the influence of past decisions in the present one. The network could be unrolled across time to yield a vanilla neural network but the parameters of this unrolled network would be tied.
Although these algorithms are very appealing in their performance promises they usually demand high resolution images, large training datasets and considerable computation resources. Nonetheless, there are reasons to believe that deep nets is an interesting perspective for smart building too for two reasons:
most of the computation effort is paid at training time not at test time. Training can be performed on standard machine and the trained network may be uploaded to the embedded system attached to the low cost camera. The occupancy detection task is much simpler than visual understanding tasks studied in computer vision. Smaller resolution images and smaller datasets may be enough for this task.

5.3.8. Speech recognition for command design

In this section, we provide a few useful references dealing with natural language processing and, more precisely, on speech recognition. Speech recognition has many potential applications for smart factories and other INCASE related topics. For instance, the production could be supervised using voice commands, which is much more ergonomic for a human operator than clicking on graphical interfaces or typing commands in a console. This is the only topic discussed in this report for which the industrial context does not imply particular specifications as compared to other contexts. In factories, there may be an increased need for robustness as this is a very noisy environment. Again, the algorithms should not consume too much energy and computation resources. But these two are not really limitative and the core ideas of natural language processing do apply.
Speech recognition is a multi-level pattern recognition challenge. The input data is a 1D signal. Depending on the semantic complexity of the information encoded in this signal, the goal of the machine may be to identify words or sentences. Each word is itself composed of a set of

[15] Survey of the state-of-the-art: Duc Thanh Nguyen, Wanqing Li, and Philip O. Ogunbona. Human detection from images and videos: A survey. *Pattern Recognition*, 51:148 – 175, 2016.

phonemes, which are basic sounds that human beings can produce. Each phoneme is a small time series containing several signal samples. Depending on the sampling frequency and on the speaker, phonemes (and consequently words) have variable lengths.
The signal processing community has produced several contributions allowing to compute feature vectors from raw signals. These feature vectors are an intermediate representation of the data. Before the deep learning breakthrough, the most popular feature extraction approach for speech signals was Mel Frequency Cepstral Coefficients (MFCCs)[16]. This method starts with a short term Fourier analysis, supposing that phonemes have approximately constant time span. Each local Fourier representation is given as input to a filter bank to evaluate the energy carried along different frequency intervals. Human cochlea (an organ in the ear) cannot disambiguate nearby frequencies. The filter bank mimics the human hearing system. This disambiguation difficulty is more prominent in high frequencies therefore the frequency interval lengths are not constant. Afterwards, one must take the logarithm of filter output energies. This is also motivated by the human hearing system for which loudness is not in linear scale. Finally, we take the discrete cosine transform of the log energies to de-correlate the feature vector entries.
Observe that an MFCC feature vector represents only one phoneme. Since words are phoneme sequences, one needs a time dependency model. The standard choice is hidden Markov models. In a more recent approach, MFCC feature vectors are used on deep recurrent neural network. This network combines the convolutional spirit of deep nets with the recurrent aspect of LSTMs. Nowadays, some deep learning algorithms have outperformed MFCC based approaches on a number of challenging datasets. Another method use a deep belief net (DBN) on feature vectors that are filter bank outputs[17]. This net is obtained by stacking generative probabilistic models known as restricted Boltzmann machines (RBMs). This net can learn a feature representation on its own. Its parameters are first obtained in an unsupervised training phase called pre-training. The output of the DBN is then connected to a deep neural net, which is trained in a supervised fashion as usual.
In summary, the main perspective of speech recognition for the problems addressed as part the INCASE project is just to adapt existing tools in the machine learning literature and not to develop a new one.

5.3.9. Automatic building regulation

Activity detection discussed in a previous section is often a building block of automatic building regulation which is a higher level task. There are many things that can be regulated in a building but most of the reported work in this field focus on heating, ventilation and air conditioned (HVAC).

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[16] Steven Davis and Paul Mermelstein. Comparison of parametric represen- tations for monosyllabic word recognition in continuously spoken sentences. *IEEE transactions on acoustics, speech, and signal processing*, 28(4):357–366, 1980.
[17] Geoffrey Hinton, Li Deng, Dong Yu, George E Dahl, Abdel-rahman Mohamed, Navdeep Jaitly, Andrew Senior, Vincent Vanhoucke, Patrick Nguyen, Tara N Sainath, et al. Deep neural networks for acoustic modeling in speech recog- nition: The shared views of four research groups. *IEEE Signal Processing Magazine*, 29(6):82–97, 2012.

Regulation consists in computing relevant inputs (or command signals) to a system so that the output of the system reaches a predefined level known as the reference signal **r**. This task is the main motivation that lead to the creation of control theory. Usually the system output is not the only one that one wishes to control. All the variables for which control is needed are stacked in a vector **s** called the state vector.

Unsurprisingly, most of the contributions that can be found in the smart building literature addressing regulation resort to control theoretic approaches and a physical model of the system. The reader is refered to the full report on the different technologies as there are linear (PID) , non-linear, model predictive, optimal or fuzzy logic based controllers, neural networks, reinforcement learning, Markov decision processes (MDPs) or extensions of it.

5.3.10. Conclusions and perspectives

In this part, we have highlighted that machine learning techniques have potential benefits in almost every aspects of smart factories and buildings. Many developments have been introduced in the machine learn- ing community over the past decade. In particular, deep reinforcement learning algorithms are a promising perspective that is likely to perform well in intelligent building control.

6. Economic impact and User acceptance

6.1. Introduction

Besides the technological challenges that a smart building requires, there also exist other ones as human acceptance and economic impact. When a solution of Smart Building starts to be studied, one of the most common question that the manager has in mind is the cost of the investment versus the financial benefit that the solution could bring.

It is not always very easy to estimate those savings, especially for large buildings. Most of the time, the electricity and heating invoices are global for the overall building and they cover a long period of time. It becomes than essential to start monitoring the current situation to have a good picture on how the heating and lighting systems are used in the building and how much effective a smart solution could be.

Another issue is the user's acceptance. When we decide to make a building "smart" to save energy, for example by a smart light and heat management, we are obliged to use some sensors, and among them, those allowing the detection of the room occupancy. When the room is a big one, knowing if someone is inside or not, does not bring any privacy problem. On the other hand, if the sensor is placed into an office, knowing if the person is inside or not, could be felt by the occupants as an opportunity to supervise their working hours. It becomes then necessary to have an appropriate communication with the staff to let them know the purpose of the smart building and to involve them actively in that process.

The Catholic University of Lille has launch in November 2013 a very ambitious project, called

LiveTree (www.livetree.fr), to contribute to the energetic transition of our region Hauts-de-France. One of the aspects of that project is the reduction of energy consumption in the buildings of the University. This report illustrates a study case of implementation of a prototype to monitor some relevant data in order to identify how the energy in a building is used. Moreover, a study about the acceptance of such a system by the building occupants was also carried out and the results are presented. The study was carried out from September 2016 to April 2017 in the ISA building, an engineering school belonging to Yncréa Hauts-de-France.

6.2. User acceptance study

First, a communication campaign was launched to explain to the ISA building occupants (students, teachers, researchers, administrators) the goal of the study and involved them in that process of changing the habits to reduce the energy consumption by using new technologies.

A logo was produced and a compelling slogan associated to it. The people were informed by mails, flyers and posters about the content of the project, the team working on it, and when the sensors were deployed in the building.

Fig. 17. Logo

The director of ISA chose to test a solution including temperature, humidity and presence sensors in order to build a heating map, measure the quality of life and encourage the staff to become actor of the energy saving process. A Google questionnaire was sent to all the ISA employers to know if they heard about the project, and if they wanted to have a sensor in their office. They were also asked about how much useful they find the use of a sensor to reduce the energy consumption. 61% of the ISA staff answered to the questionnaire. 98% declared as being concerned by the the energy saving problems. 91% accepted to have a sensor in their office. Only 11% are not convinced by the added value of a smart building. Now that the staff is informed about the aim of the project and are ready to see in the building sensors to monitor temperature, humidity and presence, we could deploy the energy-monitoring prototype.

6.3. Low cost energy monitoring prototype to evaluate the economic impact

A portable solution to deploy a network of intelligent sensors on any type of building was developed. The aim being to be able to increase the number of sensors and the types of sensors, and thus to install this solution in any building at a lower cost. The data collected are stored in the cloud and available for data processing. They can be visualised on a HMI using a tablet. To do this, different types of sensors, communication protocol and data storage with

constraints, quality price ratio and environmental impact was researched. After considering the different types of sensors available on the market, the focus was on our implementation of collection services on the Z-Wave protocol especially for cost reasons. As described in the chapter on communication, there are a large number of sensors operating on this protocol coming from various manufacturers (Fibaro, Aeotec ...) and providing useful data for the building's energy instrumentation (temperature, brightness, presence, humidity, etc.).
Z-Wave is a dedicated wireless data transmission protocol for home automation. The theoretical range of the Z-Wave is 40 meters, but this network has the possibility to be extended thanks to the mesh network. Each sensor of the network can serve as a "relay" to another sensor to the base station processing the data, thus extending the theoretical scope. In order to be able to send the data to the server available in the cloud, the sensors are connected to a RaspberryPi associated with a Sigma-Designs chipset connected to its GPIO ports allowing the transmission of the data to a server using a AMQP protocol. The normal use of the Z-Wave protocol is the domotisation of a classical home. In order to ensure a flexible installation on any building, we have devised a system in which several controllers independently manage a set of sensors and carry all the data to an external server.

6.4. Server management

Our objective is to propose an infrastructure designed as a true platform allowing the development of web interfaces, the management of the sensors network and the data analysis. In order to deploy the necessary applications for the implementation of this infrastructure on the server, we used the Docker containers technology. Among these applications, we have deployed a development platform and APIs for managing the topology of sensors networks, database, data management and analysis and web technology for displaying information.

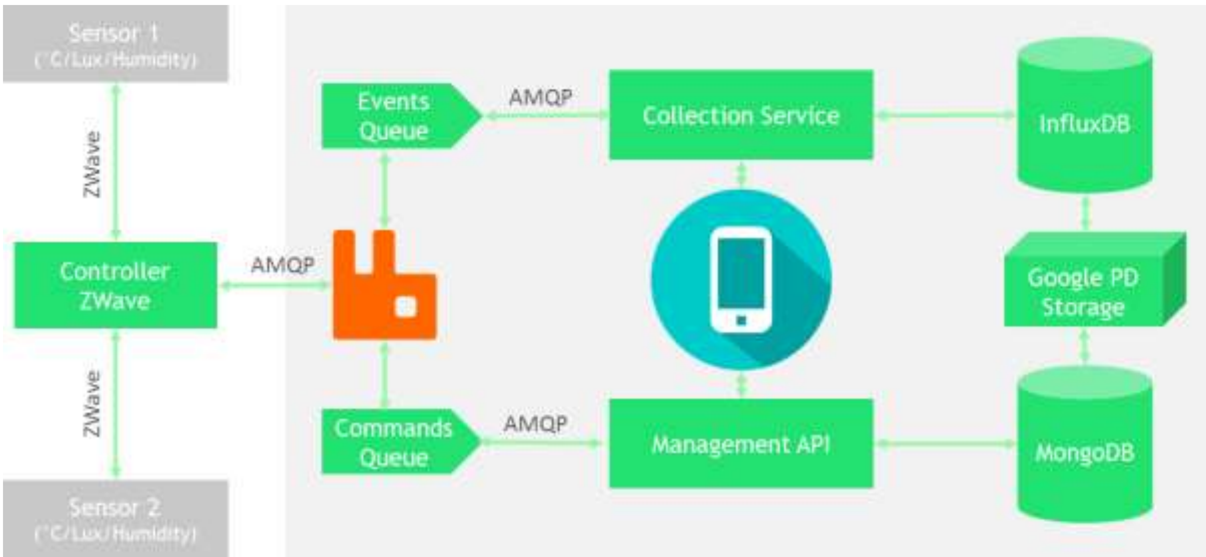

Fig. 18. Prototype architecture

A small prototype has been installed at the ISA building. It has 4 sensors assigned in a various locations: classroom, office, corridor and amphitheater. We analyzed 4 parameters: temperature, humidity, luminosity and movement. Each graphic indice was displayed via http://www.smart-isa.fr/dashboard/ website. As mentioned above, if we want to increase the type or number of sensors, this will have no significant impact on our infrastructure. Our solution is portable and suitable for scaling.

Fig. 19. Test bed of low cost energy monitoring prototype

6.5. Conclusion and perspectives

The aim of this work was to identify how the staff copes with a smart building and involve them in that transformation. Moreover, an energetic diagnosis prototype has been designed and deployed in the ISA building. We focused on the hardware and software technology to develop a sensor network, a communication protocol, data storage and analysis, and web development interface. All technologies used on this solution, allow to define a portable and scalable prototype energy building monitoring.

The future developments concern data recording and analysis during a long period (some weeks) in order to be able to identify, using a low cost prototype, how the energy is consumed in the building and if a large deployment of sensors could have an important impact in energy savings, and by result a large economic impact.

Moreover, a CO_2 sensor will be also used to measure and alert the staff on their quality of life. A HMI will be proposed to show which area in the building represents a waste energy (heating or light, door or window open, isolation, the occupant's behaviours...).

The central question of our future work is: "where should we put in place energy savings to make the buildings respectful of the occupants and the environment ?". Our response will be the development of massive data processing mixing a data mining algorithms, statistical methods and machine learning techniques.

It should also be noted that much of this work has been dedicated to communication. Indeed, the large part of ISA staff accepted to be actors for deploying the energy monitoring prototype and made this project innovative.