‚Smart Building'trends – a comparison of wireless standards for automation and control

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1 Introduction

Building automation is on the advance. Systems are becoming increasingly sophisticated, offering more and more value-added service features thanks to IT-based systems which surpass what room-/building-management systems could offer until now. These systems are heavily reliant upon data from within spaces and buildings, which can easily be gathered and transmitted by means of wireless technology.

The proliferation of building automation is supported by two trends. On the one hand, „Smart Home" systems stimulate interest and generate demand for similar solutions in commercial spaces such as offices and public buildings.

On the other hand, it has become widely accepted that buildings can be used more efficiently by intelligently interpreting usage data. Energy can be utilised more efficiently and investments in smart technology can be amortized within the space of a few years [Becker 2007]. Existing space can also be used far more efficiently, e.g. for flexible workspaces in open-plan offices, meeting rooms and sales showrooms. However, excessive usage must be avoided in order not to irritate workforce and clients alike. Last but not least, **value-added services** are playing an increasing role in making workplaces more attractive and enhancing employee productivity.

All these factors contribute towards a major shift from conventional architecture to „Smart Buildings". However, one must differentiate between **room-automation and facility automation** on the one hand, and **value-added services** in „Smart Buildings"on the other hand.

The typical **room-automation and facility automation** scenarios are intended to optimise lighting, shading and HVAC according to momentary requirements. They constitute a relatively simple but essential step on the road to more „intelligent" solutions. Here, programming is based upon relatively simple criteria in order to simplify installation and maintenance. Conventional technologies offer little support for more complex, adaptive/self-learning solutions. So-called bus systems rely upon a combination of device parameters and sensor-to-actuator interaction. This simplifies implementation but does not make for truly „smart" buildings. More sophisticated scenarios require controllers (aka server or DDC[1]) which must be programmed.

Although there is no fixed requirement to adopt a specific type of programming for building automation applications, most players in this market appear to have an affinity for the IEC 61131 standard - originally developed for programmed-memory control systems in the field of process automation, with a broad range of programming variants offering free and creative options. However, complex requirements can quickly lead to confusing programming results incompatible with ease of maintenence. In the best of cases, one selects a supplier who offers a functional programming library - but then becomes dependent upon the supplier and has to take a gamble upon his willingness to maintain the library in the long term.

Illustration 1 shows a typical three-level building automation solution. It can be seen that part of the „intelligence" is deferred from the Automation (controllers) and the Field (bus system) levels to the Management level. This level typically supervises, optimises, controls and visualises the building

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[1] Direct Digital Control

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management control system. It is not well suited to carrying out upcoming control functions. Therefore, new Building Management Systems (BMS) are being rolled out: they will allow for the random programming of „Smart Building" systems using modern IT languages and tools, interfacing with other IT systems such as room reservation systems or data banks, featuring visualisation for „normal" users (and not only facility managers) whilst offering location-based services such as in-building navigation. Such BMS systems allow for the intelligent evaluation of sensor-generated data and feature AI (Artificial Intelligence) tools. Moreover, the user can already decide whether to operate cloud-based or server-based solutions.

The vast majority of the system requirements outlined in Chapter 3 can be better - or only - fulfilled by IT-based BMS solutions.

Building automation hierarchy
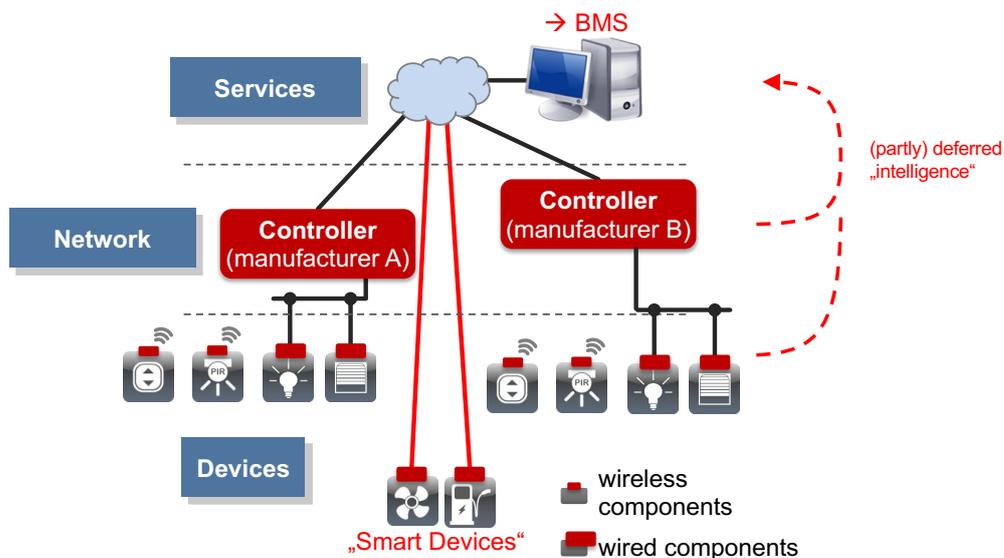
Illustration 1: Multi-level building automation system incl. deferred „intelligence"

The use of novel BMS systems allows for new **value-added services**. The evaluation of sensor data plays a key role and will lead to more intense sensor data usage than is currently the case. A true „Smart Building" makes use of economically viable, integrated sensors. They can be connected by conventional cables, or by wireless technology. This offers free sensor placement and simple installation/retrofitment. As far as the fear of so-called „electrosmog" goes, there is little to worry about – the sensors transmit very small data packages, and only as needed. Moreover, there is ample distance between persons and devices such as switches, presence sensors, window contacts etc.. Therefore, wireless sensors emit far

less „electrosmog" than always-on devices such as mobile phones, chargers, Bluetooth headsets or WLAN access points

Cable-connected devices will not be wholly supplanted. However, the diffusion of wireless devices will increase dramatically. Especially where there is a need to place sensors in objects or surfaces that need to be moved, e.g. in open-plan offices with mobile partitions. Therefore, wireless standards for the integration of sensors in automation and control applications will find more and more opportunities in the field of building automation.

This document aims to compare different wireless technologies within this context. Use Cases are described in Chapter 2. Functional requirements for each wireless standard are described in Chapter 3. Common wireless standards are described in Chapter 4, whilst Chapter 5 evaluates and compares the suitability of each wireless standard for each type of „Smart Building" application.

2   Use Cases in modern buildings

*Building automation is the key to needs-driven, energy-efficient utilisation of modern buildings. Room-automation and facility automation call for a differentiated approach, whereby the development of **value-added services** is gaining speed. These services are based upon an intensive usage of sensor data – not only for optimal resource and energy management, but also to improve workplace attractiveness and employee productivity. Use Cases indicate the type of sensor best suited to a given application, and the sensor characteristics allow us to draw conclusions concerning the most suitable wireless standard for the application in question.*

To compare wireless standards later on in this document, one must first define what needs to be automated in order to define the best solution amongst the various wireless standards available. We shall therefore list the requirements for room-automation and facility automation on the one hand, and the requirements for „Smart Buildings" on the other. The following tables also indicate the type of sensor required for each application. The type of actuator will not be contemplated here, since it is of lesser relevance for the choice of wireless standard. Also, most actuators are connected/powered by cable.

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2.1 Typical automation examples

Here are some typical automation examples, as determined by the „Planning process for Smart Home & Smart Office" [IGT 2015] survey and the DIN EN 15232 [EN15232 2017] standard for facility automation.

2.1.1 Room automation

Use Case	Devices required
Room temperature can be individually regulated depending upon occupancy and window/door status.	Temperature sensors & controllers, occupancy sensor, window/door contacts, rotary handle sensors
Room ventilation and cooling can be individually regulated, taking temperature, air quality (CO_2 and/or VOC loads) and humidity into account. Additionally, occupancy and window/door status may be taken into account	Room temperature sensors, air quality sensor, humidity sensor, occupancy sensor, window/door contacts, rotary handle sensors
Room lighting can be individually dimmed. Switches for single lights or groups of lights. Additionally, occupancy and outdoor light levels may be taken into account.	Switches, light sensor, occupancy sensor
Sunblinds/shutters for balconies & terraces stay open as long as the relative doors remain opened (lock-out protection).	Switches, rotary handle sensors (window/door contacts)
Sunblinds/shutters are governed in function of room temperature (thermal protection). Can be deactivated in case of human presence.	Temperature sensor, occupancy sensor
Sunblinds/shutters & awnings can be retracted in windy or stormy conditions.	Weather station (wind sensor)
Windows/doors can be monitored (burglary protection). Intruder protection for external areas with illumination & alarm functions.	Window/door contacts, external motion sensors
Switches for lighting/shading can be freely positioned, allowing for easy repositioning of partitions and furniture. Handheld transmitters can also be used.	Switches, handheld transmitters
Energy consumption of individual appliances, rather than the whole electric circuit, can be monitored.	Electricity meter

Table 1: Use Cases - room automation

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2.1.2 Facility automation

Use Case	Devices required
Heating and cooling for individual rooms can regulated depending upon occupancy and window status.	Temperature sensors & controllers, occupancy sensor
The supply of warmth for heating systems or refrigeration for cooling systems can be regulated to match current and projected system demands (including criteria for flow temperatures and pump rotation speed regulation).	Temperature sensors, pressure sensors
Multiple heat/cold-generating units can be governed according to system performance requirements and loads.	- (no particular sensors necessary)
Simultaneous operation of heating and cooling systems can be avoided.	- (no particular sensors necessary)
Ventilation can be regulated according to demand (taking air quality/humidity in consideration).	Air quality sensor, humidity sensor
Heat regeneration for ventilation systems can be configured to avoid icing and overheating.	Pressure sensors, temperature sensors
Fault alarms, operating hours and energy consumption can be protocolled and evaluated.	Various analogue-/binary-input sensors, electricity & water meters
In Summer, overheated buildings can be cooled economically and efficiently by ventilating with cool air at night.	Temperature sensors, external temperature sensor (or weather station)

Table 2: Use Cases - facility automation

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2.2 Additional value-added Smart Building features

As already mentioned - systems are becoming increasingly sophisticated, offering more and more value-added service features thanks to sensor data evaluation by IT-based systems which surpass what room-/building-management systems could offer until now. This offers different types of benefits. On the one hand, we have considerable energy savings through systems which repay initial investments in the space of just a few years. On the other hand, we have added value through more attractive workplaces as an incentive for recruiting and retaining employees. Together with higher employee productivity, which can bring financial rewards beyond the (more easily quantifiable) ones stemming from lower energy consumption. The following Use Cases stem from a check list published by the Institut für Gebäudetechnologie [IGT 2019] and a dissertation by Dominik Hüttemann at the Hochschule Rosenheim [Hüttemann 2020]. These Use Cases are merely examples of what „Smart Buildings" make possible. Many more solutions are under development and entering the market - the ones shown here illustrate the benefits available today for those who choose advanced, easily installed and technically mature solutions.

Use Case	Devices required
The smartphone-based dynamic booking/release of conference-room facilities. Meetings finishing ahead of schedule can be recognized and taken into account for optimal facility management.	Occupancy sensor (or activity monitor)
Individual workplaces in open-plan offices can be booked/released by smartphone. Unoccupied workplaces can be recognized and reassigned.	Table/chair occupancy sensors
Occupancy sensors can be used to analyze the use of meeting rooms , recognize resource usage patterns, protocol no-shows, manage workspace efficiently and organize catering services	Occupancy sensor or activity monitor, floor pressure sensors
The analysis of usage patterns enables the flexible allocation of employee workspace. Unutilized areas can be set to energy-saving mode, thereby cutting heating/cooling/electric power costs	Occupancy sensor or activity monitor, floor pressure sensors, table/chair occupancy sensors
Building occupancy can be displayed graphically by employing „Heat Maps" or „Moving Trails" illustrating how many persons are occupying which areas. Such insight provides the perfect basis for zone planning purposes (e.g. room size, position of meeting rooms etc.).	Occupancy sensor or activity monitor, floor pressure sensors

Table 3: additional value-added Smart Building features (part 1)

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Use Case	Devices required
Light colour can be influenced in order to enhance employee biorhythms (Human Centric Lighting - HCL). Manual override influencing the colour and intensity of light can be governed by smartphone applications or dedicated switches.	Switches, light sensor, occupancy sensor
Employees and visitors can be easily guided through the building complex, making orienteering simpler in unfamiliar facilities e.g. when looking for a specific meeting room. Project teams can be brought together, and buildings can be selectively occupied in order to reduce energy needs for unused areas. Users can express individual preferences, e.g. vicinity to lifts/stairs, specific colleagues, meeting areas or barrier-free access.	(no particular sensors necessary; use of smartphones to acquire signals from wireless beacons or measure WLAN signal strength)
Canteen usage (i.e. foreseeable waiting times) can be monitored and visualised from the workplace.	Occupancy sensor or activity monitor, floor pressure sensors
The frequency of washroom usage can be monitored and translated into appropriate cleaning schedules.	Door contacts; alternatively, sensors for handtowel/soap dispensers, water taps
Usage of lifts, coffee machines etc. can be monitored and translated into adequate maintenance schedules.	Ideally, connection with appliance data via interface - alternatively, various analogue-/binary-input sensors
Sensors within the building automation network monitor pumps, cleaning machines, HVAC systems, lifts etc. and report any malfunction in real time for better fault-finding and more efficient pre-emptive measures.	Ideally, connection with appliance data via interface - alternatively, various analogue-/binary-input sensors
The position of moveable objects can be monitored. In case of removal, alarm can be given and theft can be prevented.	Vibration detection sensor (transmits data when moved); alternatively, tracking signal transmitted at regular intervals enables indoor tracing.
Precise information for rescue teams concerning the whereabouts of people inside the building, enabling fast and efficient evacuation (e.g. in case of fire).	Occupancy sensor or activity monitor, floor pressure sensors

Table 4: additional value-added Smart Building features (part 2)

3   Wireless standard requirements

The demands that wireless standards have to meet stem from the requirements of „Smart Building" Use Cases. Further requirements arise from the need to set up, run and maintain the necessary infrastructure. This chapter analyzes these requirements as benchmarks for the suitability of the various wireless standards, as explored in later chapters.

3.1   System requirements due to the necessary sensors

The previous chapter illustrates which Use Cases require what type of sensor, as shown in Table 5. Taking Tables 1 to 4 into consideration, we can see that most sensors have to fulfil a variety of roles. Therefore, good market availability and ease of system integration are of great importance for a broad range of applications.

Therefore, wireless standards must ideally support a broad range of freely available sensors.

Table 5 also illustrates data volume, data transmission frequency rates and time criticality. This information plays an important role when determining the suitability of individual wireless standards.

The split into Low/Middle/High ratings is based upon the following considerations:

Data volume
How large ist the quantity of data that needs to be transmitted?
- **Low**   1 – 10 Bytes
- **Middle**   11 – 100 Bytes
- **High**   101 – 1000 Bytes
- **Very high**   > 1000 Bytes

Data transmission frequency rates
On average, realistically, how often does data have to be transmitted?
- **Low**   less than 1x per quarter of an hour
- **Middle**   more than 1x per quarter of an hour
- **High**   more than 1x per minute
- **Very high**   more than 10x per minute

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Time criticality

How quickly must data be transmitted? Higher transmission rates demand shorter wireless network latency times.

- **Low**   from 1 to 60 minutes
- **Middle**   from 1 to 60 seconds
- **High**   faster than 1 second
- **Very high**   faster than 0.1 second

Sensor	Data volume	Frequency rate	Time criticality
Activity monitor	Low	Middle	Middle
External motion sensor	Low	Middle	High
External temperature sensor	Low	Low	Mittel
Floor pressure sensor	Low	High	High
Various analogue-/binary-input sensors	Low	Depending upon sensor values	Depending upon sensor values
Rotary handle sensor	Low	High	High
Pressure sensor	Low	Middle	Middle
Vibration detection sensor	Low	Middle	Middle
Light sensor	Low	Middle	High
Air humidity sensor	Low	Middle	Middle
Air quality sensor	Low	Middle	Middle
Occupancy sensor	Low	Middle	High
Room temperature sensor/ roomtemperature controller	Low	Middle	Middle
Sensor for handtowel/soap dispenser, water tap	Low	Middle	Low
Electricity & water meters	Middle	Low	Low
Switches, handheld transmitters	Low	High	High (bordering on „very high")
Temperature sensor	Low	Middle	Middle
Door/window contacts	Low	High	High
Weather station (wind, temperature, humidity)	Middle	Middle	Middle

Table 5: sensor overview

3.2   Criteria for determining suitability

This section explores the individual criterion which renders a given wireless standard more - or less - suited to applications in a „Smart Building" environment, as outlined in Chapter 2.

Suitability of the frequency band (KO criterion)
The previous chapters illustrate what is ideally required of a wireless standard according to the type of sensor in use (see Table 5).

The Use Cases listed in Chapter 2 outline which type of sensor is required in order to implement **room-automation** and **facility automation** solutions as well as **additional value-added Smart Building features**. Die parameters illustrated in Chapter 3.1, on the other hand, define the system requirements due to the necessary sensors. All in all, we can therefore define the requirements for data transfer.

It has been shown that connecting sensors does not require high data transmission frequency rates. The amount of data (telegram packet size) to be sent at any one time is usually quite small, and even „intensive data transmission"is usually limited to max. 10 data packets/minute. Meaning that wireless protocols should ideally use small data packets in order to minimise redundant (and inefficient) transmission capacity.

Data transmission rates are mostly unproblematic. Latency times under 1 second are usually only required when immediate response is needed (e.g. when a switch is operated, when entering a room or when a door or window is opened), and even then 0.1 second is mostly sufficient.

As far as range goes, in many instances sensor-generated data must initially reach a controller or gateway since the signal must first be processed at automation or management (BMS) level - see **Error! Reference source not found.**. Sensors are typically located throughout a building, and usually require an appropriate infrastructure (e.g. cable-connected antennas for receiving signals from wireless „satellite"sensors in the vicinity). The greater the range of the wireless devices employed, the larger the „Catchment Area" becomes - requiring a smaller number of antennas and a leaner, cheaper infrastructure.

Transmitter power is another important consideration. Mains power requires cables, and cables are a limiting factor for sensor placement. Most sensors are therefore battery-powered or self-powered. This means that energy must be used as efficiently as possible, with no technical „frills"- hence: small data packets (approx. 10 bytes, as already outlined), latency times between 0.1 and 1 second and adequate range (typically between 10 m and 100 m).

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The suitability comparison of wireless standards in Chapter 5 takes the following classification into account:

- **Low**: high data transmission rates (e.g. in Mbit/Mbits-range); insufficient/excessive range (e.g. < 10 m or > 100 m) resulting in excessive power consumption; latency > 1 s;
- **Middle**: low data rates and data packets > 100 bytes and latency > 1 s (preferably 0.1 s); range 10 m - 100 m; high energy consumption.
- **High**: low data rates and data packets > 100 Bytes and latency > 1 s (preferably 0.1 s); range 10 m - 100 m.

Important

„Suitability of the frequency band"is a KO-criterion.

This means that the overall suitability ranking for a given wireless standard will not exceed the value attained in the "Suitability of the frequency band" rating. Inadequate basic data transmission characteristics of a given frequency band lead to its negative overall rating.

Manufacturer dependence

In the best interests of the user, wireless standards should operate across as many suppliers as possible. Wireless technology should be standardised in order to allow for maximal interoperability between devices produced by different suppliers.

The suitability comparison of wireless standards in Chapter 5 takes the following classification into account:

- **Low** (0 points): standardised wireless protocol; all components for sensor manufacturing are available from numerous suppliers. Sensor devices are available from numerous suppliers, interoperability guaranteed.
- **Middle** (1 point): standardised wireless protocol; some components for sensor manufacturing are only available from one supplier. Sensor devices are available from numerous suppliers, interoperability guaranteed. Alternative: dependency upon fee-based provider services.
- **High** (2 points): non-standardised wireless protocol; components/sensors only available from one supplier; no/restricted interoperability.

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Infrastructure

In Smart Buildings, devices and actuators are usually governed by a central system e.g. a controller or an IP-based management system via gateway access (see illustration 1). Limited wireless sensor range calls for differing infrastructure demands.

The suitability comparison of wireless standards in Chapter 5 takes the following classification into account:

- **Infrastructure** and/or **Mesh** (1 point each): buildings must possess their own infrastructure e.g. cable-connected antennas and gateways which convert wireless signal packets into data for cable transmission to management systems. Alternatively, the wireless protocol allows for meshed communication between devices - i.e. forwarding of data telegrams via intermediate nodes (intermediate components, with higher energy consumption necessitating mains power connection).
- **No own infrastructure** (2 points): longer-range signal transmission eliminates the need for own infrastructure. Particularly advantageous with a low sensor network density, where setting up an own infrastructure would be relatively costly.

Integrability

Smart Buildings require that sensors be integrated into higher-level systems (controllers, DDC etc.) or connected via gateway. Including data transfer to IP-based protocols, if the sensors are not IP-compatible.

The suitability comparison of wireless standards in Chapter 5 takes the following classification into account:

- **Low** (0 points): very few or no interfaces/gateways available for products from the main controller suppliers, no (or hardly any) gateways.
- **Middle** (1 point): very few or no interfaces/gateways available for products from the main controller supplier; no (or hardly any) gateways. Few coupling options available. Alternatively, IP-based „alternate routing" required (with increased latency times).
- **High** (2 points): multiple controller suppliers offer broad protocol support, good gateway availability. Proven reference project information.

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Broad availability of the necessary hardware components

Table 5 shows the many different types of sensors required by typical Use Cases in „Smart Buildings". Here, we take commercial availability into account (with type number/data sheet, as well as manufacturer warranty and repair issues).

The suitability comparison of wireless standards in Chapter 5 takes the following classification into account:

- **Low** (0 points): sensors for Smart Building applications are only commercially available as rudimentary components.
- **Middle** (1 point): the majority of sensors for Smart Building applications are commercially available
- **High** (2 points): all - or nearly all - sensors for Smart Building applications are readily available.

Measuring and testing

In order to guarantee trouble-free running of automation systems, wireless data analysis must be possible. Measuring and testing equipment, as well as user documentation, is required.

The suitability comparison of wireless standards in Chapter 5 takes the following classification into account:

- **Low** (0 points): no adequate measurement or testing possible (no equipment/documentation available).
- **Middle** (1 point): measurement/testing possible. Equipment hard to obtain, expensive or complicated to use.
- **High** (2 points): easy-to-use measuring and testing equipment/documentation & tutorials readily available.

Power supply

The main advantage of wireless technology is the free positioning of devices. Mains power connection is an obvious hindrance. A low sensor density allows for the use of battery-powered devices, assuming a multiannual battery life in order to minimize maintenance. Self-powered (e.g. photovoltaic) devices offer clear benefits. Low energy consumption is important, for each type of device.

The suitability comparison of wireless standards in Chapter 5 takes the following classification into account:

- **External power supply** (0 points)
- **Battery-powered** (1 point)
- **Self-powered** (2 points)

Data encryption

Data encryption and security aspects are becoming ever more important and influence the quality standards of data transmission. This is especially true of wirelessly-governed actuators. Integrity of sensor data transmission is less critical. However, data encryption should be contemplated in all cases.

The suitability comparison of wireless standards in Chapter 5 takes the following classification into account:

- **Low** (0 points): no data encryption possible
- **Middle** (1 point): support for mid-level data transfer security
- **High** (2 points): support for high-level data transfer security

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4 Overview of available wireless standards

In this Chapter we explore the various wireless protocols available at present and foreseeable future times. Each protocol is briefly described in profile. To begin with, let's take a look at the relevant frequency bands.

4.1 Frequency bands

High-frequency data transmission takes place within set frequency bands.

Smart Building sensors operate on UHF (Ultra-High Frequency ; 0.3 GHz – 3 GHz) and SHF (Super-High Frequency; 3 GHz – 30 GHz) bands. The following tables show the relative European sub-frequency bands - US and Asian markets use different frequencies.

Frequency	Designation	Comments
433 MHz, 868 MHz	SRD (Short Range Devices)	Licence-free; time-limited transmission (e.g. 868.3 MHz e.g. 1%), max. transmission power for 863 MHz - 869 MHz: 25 mW
2.4 GHz	WLAN, Bluetooth, Thread, ZigBee	Licence-free; max. transmission power 100 mW
0.7 GHz – 2.1 GHz; 2.6 GHz – 3.6 GHz	Cellular networks (2G, 3G, 4G)	Various frequency bands for GSM (2G), UMTS (3G) and LTE (4G). Usage requires licence, with provider fees. Max. transmission power varies between 2 W (2G) and 0.2 W (4G).

Table 6: UHF frequency bands and selected sub-frequencies

Frequency	Designation	Comments
5.1 – 5.7 GHz	WLAN	Licence-free; max. transmission power 1000 mW.
ab 3.4 GHz	Cellular network (5G)	5G cellular technology uses various frequencies. First applications in the so-called C-Band (3.4 GHz – 3.7 GHz) range. Higher frequencies foreseen for later applications. Usage requires licence, with provider fees.

Table 7: SHF frequency bands and selected sub-frequencies

4.2   Overview of available wireless standards

The wireless protocols outlined here are the ones best suited to connecting sensors and applications in the field of building automation and the IoT (Internet of Things).

The relative descriptions follow this structure

- General describtion (aim/suitability)
- Suitability of the frequency band
  (data volume, latency times, packet size, range, transmitting power/energy consumption)
- Manufacturer dependence; standardization
- Infrastructure; licences; Mesh; ad hoc
- Integrability
- Commercial availability of devices
- Measuring and testing
- Power supply
- Encryption

4.2.1   5G cellular network

The 5G (5th generation) cellular network standard was developed in order to improve upon LTE (4G) network coverage and performance. It offers potential when sensors cannot be easily connected to an own network infrastructure, or where doing so would involve disproportionate cost due to low sensor density.

Data transfer rates of more than 1 Gbit/s are to be expected, with latency times in the range of a few milliseconds. Range depends upon the frequency used and the level of infrastructure in place, with a typical range of a few hundred metres.

The protocol is standardized, with no user device manufacturer dependence. Interoperability between devices from different suppliers is guaranteed. However, the use of provider services is subject to fees. Direct data transfer between devices is not foreseen - connection only via provider infrastructure.

The integration of user devices with building automation controllers (DDC systems) only possible via the connection of DDC systems with the provider platform.

5G-compatible building automation devices e.g. switches, occupancy sensors, door/window contacts etc. - see Table 5 - are not yet on the market (and future availability remains to be seen).

Measuring and testing equipment for 5G technology is basically available but expensive and requires skilful operation/training. It is unlikely that the average system integration technician would possess - or be able to operate - such equipment.

We can assume that sensors will be either mains-powered or battery-powered (rechargeable or replaceable). More accurate predictions are not possible, as the necessary hardware is mostly under development.

High-level data encryption will be supported.

4.2.2 Bluetooth / BLE (Bluetooth Low Energy)

Bluetooth and BLE were developed with short-range (Personal Area Networks = PAN) communication, at middle data transmission rates, in mind. Bluetooth is especially popular for audio communication between smartphones/tablets and peripheral devices (speakers, headphones, hands-free units) and is universally supported. The energy-optimized Bluetooth Low Power (BLE) version was developed with the transfer of small data packets between sensors and smartphones - especially in the field of sport - in mind. BLE could also be imployed in a Smart Building context.

BLE supports data rates up to 2 Mbit/s with very small latency times (below 100 ms). Data packet size varies between 10 Bytes and 255 Bytes. Max. outdoor line-of-sight range is approx. 50 m; indoor range is typically 10 m - 15 m. Transmitting power is limited to 100 mW, whereby some sub-standards allow up to 10 mW.

The Bluetooth Protocol is published and curated by the Bluetooth Special Interest Group (SIG) as a hierarchical set of standards. Some applications - such as audio data transfer - have achieved total interoperability across users and applications. However, this is not yet the case for building automation applications.

Bluetooth devices can communicate directly amongst themselves, and with an overriding infrastructure. Mesh network structures are also supported (Bluetooth Mesh), where information is relayed by a number of Bluetooth devices (provided they are no more than 10 m apart and can support an increased energy consumption).

The integration of Bluetooth devices in controllers for building automation systems (DDC systems) is possible via Bluetooth interfaces provided by some manufacturers; alternatively, integration via Bluetooth IP gateways is possible (with an appreciable increase in latency time).

More and more Bluetooth sensors for building automation are gradually coming to market - however, it will be some time before a full range of devices as outlined in Table 5 becomes available.

Measuring and testing equipment, plus the relative user documentation, is readily available at reasonable cost.

Currently available Bluetooth sensors are either mains or battery-powered. Self-powered devices are under development.

Various encryption solutions are available, offering high-level data security.

4.2.3   EnOcean

The EnOcean wireless protocol was explicitly designed with self-powered devices („Energy Harvesting") in mind, with special focus on building automation.

In Europe, EnOcean operates on 868,3 MHz and therefore within the SRD frequency range - suited to transmitting short data packets (see Chapter 4.1). Data can be transmitted at a rate of 125 kbit/s. With extremely short latency times which, in practice, cannot be sensed even when using time-critical devices such as switches. Data packet sizes can vary between 7 Bytes – 16 Bytes. Max. indoor range is in the region of 30 m. In keeping with the SRD standard, transmitting power is limited to 25 mW.

The EnOcean protocol is internationally recognized as ISO/IEC standard, and a high degree of interoperability is guaranteed across devices from a broad range of suppliers using the interoperable profiles created by the EnOcean Alliance - an open, non-profit organization with 400+ companies primarily operating in the field of building automation.

EnOcean devices can communicate directly amongst themselves, and with an overriding infrastructure.

The integration of EnOcean devices in building automation (DDC system) controllers is facilitated by the provision of EnOcean interfaces by many manufacturers; alternatively, other gateway solutions (e.g. EnOcean-IP, EnOcean-KNX, EnOcean-DALI etc.) are available.

A broad range of sensors for building automation applications is readily available from multiple suppliers.

Measuring and testing equipment, plus the relative user documentation, is readily available at reasonable cost.

The vast majority of currently available EnOcean sensors are self-powered (photovoltaic, energy converter etc.)

Various encryption solutions are available, offering high-level data security.

4.2.4 KNX RF

The KNX RF (KNX Radio Frequency) wireless protocol is published and curated by the KNX Association as addition to the classic cable-based KNX protocol, with special focus on building automation.

In Europe, KNX RF operates on 868,3 MHz and therefore within the SRD frequency range - suited to transmitting short data packets (see Chapter 4.1). Data can be transmitted at a rate of 16 kbit/s. With extremely short latency times which, in practice, cannot be sensed even when using time-critical devices such as switches. Data packet sizes can vary between 8 Bytes – 23 Bytes. Max. indoor range is in the region of 30 m. In keeping with the SRD standard, transmitting power is limited to 25 mW

The KNX RF protocol is internationally recognized as ISO/IEC standard, and a high degree of interoperability is guaranteed across devices from a broad range of suppliers. Suppliers must be members of the KNX Association, and their products must be certified by the Association prior to market launch.

KNX-RF devices can communicate directly amongst themselves, and with an overriding infrastructure.

The integration of KNX RF devices in building automation (DDC system) controllers is enabled by the conversion from KNX RF to KNX TP (Twisted Pair, cable-bound) protocol in intermediate nodes. Limited range calls for the multiple use of such nodes in larger buildings, connected to one or more KNX controller (or controllers with KNX interface, or KNX gateways) by KNX TP bus cables .

Sensors for building automation applications are available from a number of manufacturers.

Analysis of the KNX RF protocol takes place via the standardized KNX installation software - provided that the necessary infrastructure is in place.

Measuring and testing equipment for KNX RF is not yet available.

Most KNX RF sensors are battery-powered.

KNX RF supports data encryption, provided that the devices used also support encryption and that the appropriate steps are taken during installation.

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4.2.5 LoRa

LoRa technology (Long Range) was developed to connect low-energy devices, usually sensors, over longer distances. They use the so-called LoRaWAN (Long Range Wide Area Network) protocol. LoRa is aimed mainly at the IoT (Internet of Things), including the field of building automation. Most applications feature a low sensor density and building-to-building outdoor communication in peripheral urban and rural areas (LoRa Alliance mission statement: „for large public networks").

In Europe, LoRaWAN operates on 868,3 MHz and therefore within the SRD frequency range - suited to transmitting short data packets (see Chapter 4.1). Data can be transmitted at rates between 0.3 kbit/s and 50 kbit/s. Data packet size can reach 64 Bytes. Latency times are not ascertainable at present, although some sources assume latency times of up to 128 seconds (!) in energy-saving mode. That might be acceptable for some applications, but not for the typical building automation Use Cases. Max. outdoor range is in the region of 2 km in urban settings. Indoor range is presently unknown, but is obviously greatly reduced. In keeping with the SRD standard, transmitting power is limited to 25 mW

LoRaWAN is not standardized. All transmitters and receivers utilize integrated circuits supplied by Semtech Corporation. LoRaWAN devices cannot communicate directly amongst themselves, only with an overriding infrastructure.

The integration of LoRa devices with building automation controllers (DDC systems) is only possible via IP-based connections. LoRa sensor information is transmitted to a central application server for conversion to IP network standard, then transmitted to the DDC system. Moreover, the LoRa application server and the DDC system must process the information (e.g. by using the MQTT protocol). So far, no evidence exists of successful LoRa implementation in large-scale building automation projects.

Sensors for building automation applications are scarcely available.

Measuring and testing for LoRaWAN applications is possible, but not at satisfactory levels for a fast and practical installation or fault-finding/debugging.

LoRa sensors are battery-powered.

LoRaWAN supports data encryption.

4.2.6 NB-IoT

NB-IoT (Narrow Band Internet of Things) is a feature of 4G cellular networks. It aims to make use of existing infrastructure for IoT applications. As for LoRa and 5G, the emphasis here is on service providers for public networks.

Data transmission takes place via 4G (LTE) network. The use of provider services is subject to licence fees. Data can be transmitted at rates between 16 kbit/s and 127 kbit/s. Data packet sizes can vary between 20 Bytes - 200 Bytes. Latency times can vary between 1.6 seconds and 10 seconds.

The protocol was published by 3GPP, a council formed by a number of industrial standard institutes, but has not been updated since mid-2016 - probably due to the advent of (and foreseeable switch to) 5G technology.

NB-IoT devices can only communicate with an overriding infrastructure.

The integration of NB-IoT devices with building automation controllers (DDC systems) is only possible via the 4G provider platform.

NB-IoT-compatible building automation devices e.g. switches, occupancy sensors, door/window contacts etc. (see Table 5) are not on the market and future availability is unlikely in view of impending 5G introduction.

Measuring and testing equipment for 4G technology and NB-IoT is basically available but expensive and requires skilful operation/training. It is unlikely that the average system integration technician would possess - or be able to operate - such equipment.

We can assume that sensors would be either mains-powered or battery-powered (rechargeable or replaceable). More accurate predictions are not possible, as the necessary hardware is not undergoing further development due to 5G.

High-level data encryption is supported.

4.2.7 Sigfox

Like LoRa, Sigfox was developed to connect devices over longer distances. This technology is sourced directly by the Sigfox S.A. company, which also acts as provider. Sigfox is aimed mainly at the IoT (Internet of Things), including the field of building automation. Most applications feature a low sensor density and building-to-building outdoor communication in peripheral urban and rural areas.

In Europe, Sigfox operates on 868,3 MHz and therefore within the SRD frequency range - suited to transmitting short data packets (see Chapter 4.1). Data can be transmitted at a rate of 100 Bit/s. Data packet size is 12 Byte. Latency times are not ascertainable at present. At a rate of max. 140 packets/day, instant transmission is of little importance. That might be acceptable for some applications, but not for the typical building automation Use Cases. Line-of-sight outdoor range is in the region of 2 km - 30 km in urban settings. Indoor range is presently unknown, but is expected to be in the order of 3 km. In keeping with the SRD standard, transmitting power is limited to 25 mW

The Sigfox protocol is not standardized. All transmitters and receivers utilize integrated circuits supplied by Sigfox S.A.. Sigfox devices cannot communicate directly amongst themselves, only with an overriding infrastructure.

The integration of Sigfox devices with building automation controllers (DDC systems) is only possible via IP-based connections. Sigfox sensor information is transmitted to a central application server for conversion to IP network standard, then transmitted to the DDC system. Moreover, the Sigfox application server and the DDC system must process the information (e.g. by using the MQTT protocol). So far, no evidence exists of successful Sigfox implementation in large-scale building automation projects.

Sensors for building automation applications are not commercially available.

Measuring and testing for Sigfox applications is possible, but not at satisfactory levels for a fast and practical installation or fault-finding/debugging.

Sigfox sensors are battery-powered.

Data encryption is supported.

4.2.8 Thread

The Thread wireless protocol was designed with a focus on connecting devices with in-building networks for building automation.

The Thread protocol operates on the 2,4 GHz frequency. Data can be transmitted at a rate of 250 Bit/s. Data packet size is 127 Bytes. Latency times beneath 100 ms can be achieved for a single transmission path. Thread is mesh-compatible; therefore end-to-end communication can take place via a multitude of intermediate steps, increasing total latency time. Max. indoor range is in the region of 10 m to 15 m. The mesh topology enables large networks. However, increased energy consumption must be taken into account. In keeping with the frequency standard, transmitting power is limited to 100 mW.

At lower levels, the Thread protocol makes use of the international IEEE 802.15.4 standard. At upper levels, it apparently supports IPv6-addressing. According to Google, Thread is an „Open Thread" specification. It can be assumed that devices complying with this specification are interoperable.

Thread devices communicate with so-called Thread Routers, which must be installed in adequate numbers throughout the building. These routers are meshed, and an interface (so-called Edge Router) is required for connection to other networks (e.g. LAN or WLAN).

The integration of Thread devices with building automation controllers (DDC systems) is similarly possible. In addition, the Thread Edge Router and the DDC system must process the information (e.g. by using the MQTT protocol). So far, no evidence exists of successful Thread implementation in large-scale building automation projects.

Sensors for building automation applications are scarce on the market.

Measuring and testing equipment for a fast and practical installation, or fault-finding/debugging, is not freely available on the market.

Thread sensors are battery-powered.

Data encryption is supported.

4.2.9 WLAN

WLAN was developed as a high-speed alternative to cabled Ethernet connection for high-performance devices, and is standardized within the IEEE 802.11 norm family.

Data can be transmitted at several hundred Mbit/s depending on the WLAN protocol in use. Typical data packet size is 2.312 Byte - this can be adjusted, but the constant size of the packet header would lead to a worsening of data transfer efficiency. Since WLAN networks can be easily installed by almost anyone, the risk of interference is high - leading to slower data transfer rates. Such interference would not prevent the transfer of individual packets, but could result in delays. Therefore, low latency times cannot be guaranteed. In keeping with the frequency standard, transmitting power is limited to 100 mW.

A high degree of interoperability is guaranteed across devices from a broad range of suppliers.

WLAN devices can, theoretically, communicate directly amongst themselves - however, they are customarily integrated into an overriding IP-based infrastructure (e.g. WLAN access points).

The integration of WLAN devices with building automation controllers (DDC systems) is only possible via IP-based connection. In addition, the WLAN devices and the DDC system must process the information. This requires the use of a technically advanced protocol, for which there is no standard or defined set of requirements. So far, no evidence exists of successful WLAN implementation in large-scale building automation projects

Sensors for building automation applications are scarce on the market.

Generic measuring and testing equipment (& software for laptop computers), plus user documentation, is readily available.

The few WLAN sensors available on the market are battery-powered.

Data encryption is supported.

4.2.10 ZigBee / ZGP (ZigBee Green Power)

The ZigBee wireless protocol was designed with a focus on connecting devices with in-building networks for building automation.

In Europe, the ZigBee protocol operates mainly on the 2.4 GHz frequency - especially as of version 3.0. Some devices operate on the SRD frequency (868,3 MHz). On 2.4 GHz, data can be transmitted at a rate of 250 kbit/s. Data packet size is 127 Bytes. Latency times for a single transmission path are extremely short and, in practice, cannot be sensed even when using time-critical devices such as switches. ZigBee is mesh-compatible; therefore end-to-end communication can take place via a multitude of intermediate steps, increasing total latency time. Max. indoor range is in the region of 10 m to 15 m. The mesh topology enables large networks. However, increased energy consumption must be taken into account. In keeping with the frequency standard, transmitting power is limited to 100 mW.

At lower levels, the ZigBee protocol makes use of the international IEEE 802.15.4 standard. At upper levels, it uses manufacturer-specific applications to the detriment of interoperability. Version 3.0 aims to improve operability across devices from different suppliers.

ZigBee devices can communicate directly amongst themselves, and with an overriding infrastructure.

The integration of ZigBee devices with building automation controllers (DDC systems) is only possible via a ZigBee IP gateway. ZigBee sensor information is transmitted via LAN to the DDC system. In addition, the ZigBee devices/gateway and the DDC system must process the information (e.g. by using the MQTT protocol). So far, no evidence exists of successful ZigBee implementation in large-scale building automation projects.

Sensors for building automation applications are available from a small number of manufacturers.

Measuring and testing equipment is available.

ZigBee sensors are battery-powered. ZigBee 3.0 also supports self-powered Energy Harvesting Modules and is marketed as ZigBee Green Power (ZGP).

Data encryption is supported. However, past data security issues prompt enhanced data security with current Version 3.0.

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4.2.11   Z-Wave

The Z-Wave wireless protocol was designed with a focus on connecting devices with in-building networks for building automation

In Europe, Z-Wave operates on 868,3 MHz and therefore within the SRD frequency range - suited to transmitting short data packets (see Chapter 4.1). Data can be transmitted at a rate of 100 Bit/s. Max. data packet size is 64 Byte. Latency times for a single transmission path are extremely short and, in practice, cannot be sensed even when using time-critical devices such as switches. Z-Wave is mesh-compatible; therefore end-to-end communication can take place via a multitude of intermediate steps, increasing total latency time. Max. indoor range is in the region of 30 m. The mesh topology enables large networks. However, increased energy consumption must be taken into account. In keeping with the frequency standard, transmitting power is limited to 25 mW.

The Z-Wave protocol is standardized, with documentation exclusively available to members of the Z-Wave Alliance.

Z-Wave devices can communicate directly amongst themselves, and with an overriding infrastructure.

The integration of Z-Wave devices with building automation controllers (DDC systems) is only possible via a Z-Wave IP gateway. Z-Wave sensor information is transmitted via LAN to the DDC system. In addition, the Z-Wave devices/gateway and the DDC system must process the information (e.g. by using the MQTT protocol). So far, no evidence exists of successful Z-Wave implementation in large-scale building automation projects.

Sensors for building automation applications are available from a large number of manufacturers. All devices use transceiver IC components from Silicon Labs

Dedicated measuring and testing equipment is available.

Z-Wave sensors are battery-powered.

Data encryption is supported.

5   Suitability comparison of wireless standards

In this Chapter we compare the wireless standards outlined in Chapter 4.2 with the requirements listed in Chapter 3.2 and evaluate the results. Each standard is summarized concisely in a „protocol profile". The resultant overall ranking is illustrated in an overview.

5.1 Wireless standard characteristics

A holistic assessment of the suitability of each protocol is structured as follows:

- For each criterion, the score attained in Chapter 0 is taken into account (e.g. for „Manufacturer dependence" 0 points for „low", 1 point for „middle" and 2 points for „high")

- The total number of points scored by each protocol is subdivided by the number of criteria being considered, resulting in the following ranking:

Ø score	Overall suitability
0.0 to ≤ 0.5	Low
0.5 to ≤ 1.5	Middle
1.5 to 2.0	High

- „Suitability of the frequency band" is a KO criterion. This means that the overall suitability ranking for a given wireless standard will not exceed the value attained in the „Suitability of the frequency band" rating.

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5G	
Criterion for determining suitability	**Score**
Suitability of the frequency band (KO criterion) Unnecessarily high data transmission rate and excessive range; therefore, excessive sensor energy consumption.	Low (0 points)
Manufacturer dependence Low manufacturer dependence; dependence on service provider, fees payable for provider services.	Middle (1 point)
Infrastructure No own infrastructure necessary, service provider infrastructure available.	No own infrastructure (2 points)
Integrability Integration of sensor data with building automation controllers (DDC systems) is only possible via an IP-based network (no direct connection possible).	Middle (1 point)
Market availability Sensors for building automation applications are not yet available.	Low (0 points)
Measuring & testing Measuring & testing equipment is available, but costly and complicated to use.	Middle (1 point)
Power supply Mains power, or battery-powered sensors.	Battery-powered (1 point)
Data encryption Data security solutions available.	High (2 points)

Overall assessment At present, unsuitable for building automation applications due to frequency band characteristics.	**Low (KO criterion)**

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BLE (Bluetooth Low Energy)	
Criterion for determining suitability	**Score**
Suitability of the frequency band (KO criterion) Data transmission rate, range and latency time within the required range.	High (2 points)
Manufacturer dependence Standardized protocol. Limited device compatibility/interoperability.	Middle (1 point)
Infrastructure Integration of sensor data requires an own infrastructure. Mesh technology can help to lower costs.	Infrastructure/ Mesh (1 point)
Integrability Integration of sensor data with building automation controllers (DDC systems) is possible directly or via an IP-based network. Many substandards hinder interoperability.	Middle (1 point)
Market availability Limited device availability for building automation applications.	Middle (1 point)
Measuring & testing Dedicated equipment, plus the relative user documentation, is available and easy to use.	High (2 points)
Power supply Mains power, or battery-powered sensors.	Battery- powered (1 points)
Data encryption Data security solutions available.	High (2 points)

Overall assessment Essentially suitable for building automation applications. However, reduced interoperability and the lack of direct integrability, as well as reduced market availability of the necessary components and the lack of self-powered sensor technology, represent major deficits.	**Middle** (Ø 1.4 points)

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EnOcean

Criterion for determining suitability	Score
Suitability of the frequency band (KO criterion) Data transmission rate, range and latency time within the required range.	High (2 points)
Manufacturer dependence Standardized protocol. High interoperability.	low (2 points)
Infrastructure Backbone infrastructure required for integration of sensor data.	Infrastructure (1 point)
Integrability Integration of sensor data with building automation controllers (DDC systems) is possible directly or via an IP-based network.	High (2 points)
Market availability A broad range of sensors for building automation automation applications is available.	High (2 points)
Measuring & testing Dedicated equipment, plus the relative user documentation, is available and easy to use.	High (2 points)
Power supply Energy Harvesting for all devices (self-powered).	Self-powered (2 points)
Data encryption Data security solutions available.	High (2 points)

Overall assessment	
Overall assessment Eminently suited for building automation applications.	**High** (Ø 1.9 points)

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KNX RF	
Criterion for determining suitability	**Score**
Suitability of the frequency band (KO criterion) Data transmission rate, range and latency time within the required range.	High (2 points)
Manufacturer dependence Standardized protocol.	Low (2 points)
Infrastructure Backbone infrastructure required for integration of sensor data.	Infrastructure (1 point)
Integrability Integration of sensor data with building automation controllers (DDC systems) only possible via a KNX-TP-based network (i.e. no direct integration).	Middle (1 point)
Market availability Limited device availability for building automation applications.	Middle (1 point)
Measuring & testing Dedicated equipment is not available. Measuring & testing require cable-based connection to wireless interfaces.	Middle (1 point)
Power supply Mains power, or battery-powered sensors.	Battery-powered (1 point)
Data encryption Data security solutions available.	High (2 points)

Overall assessment Essentially suitable for building automation applications. However, reduced availability of measuring & testing equipment and the lack of direct integrability, as well as reduced market availability of the necessary components and the lack of self-powered sensor technology, represent major deficits.	**Middle** (Ø 1.4 points)

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LoRa	
Criterion for determining suitability	**Score**
Suitability of the frequency band (KO criterion) Extremely high latency times.	Low (0 points)
Manufacturer dependence No standardized protocol. All devices use single-source IC components.	High (0 points)
Infrastructure Backbone infrastructure required for integration of sensor data. LoRa networks are used in some urban ares as an alternative, provider-dependent solution.	Infrastructure (1 point)
Integrability Integration of sensor data with building automation controllers (DDC systems) is only possible via an IP-based network (no direct connection possible).	Middle (1 point)
Market availability Sensors for building automation applications are not yet available.	Low (0 points)
Measuring & testing Measuring & testing equipment is available, but complicated to use.	Middle (1 point)
Power supply Mains power, or battery-powered sensors.	Battery-powered (1 point)
Data encryption Data security solutions available.	High (2 points)

Overall assessment At present, unsuitable for building automation applications due to frequency band characteristics.	**Low (KO criterion)**

NB-IoT

Criterion for determining suitability	Score
Suitability of the frequency band (KO criterion) Unnecessarily high data transmission rate and excessive range; therefore, excessive sensor energy consumption. High latency times.	Low (0 points)
Manufacturer dependence Low manufacturer dependence; dependence on service provider, fees payable for provider services.	Middle (1 point)
Infrastructure No own infrastructure necessary, service provider infrastructure available.	No own infrastructure (2 points)
Integrability Integration of sensor data with building automation controllers (DDC systems) is only possible via an IP-based network (no direct connection possible).	Middle (1 point)
Market availability Sensors for building automation applications are not yet available.	Low (0 points)
Measuring & testing Measuring & testing equipment is available, but costly and complicated to use.	Middle (1 point)
Power supply Mains power, or battery-powered sensors.	Battery-powered (1 point)
Data encryption Data security solutions available.	High (2 points)

Overall assessment At present, unsuitable for building automation applications due to frequency band characteristics.	**Low** **(KO criterion)**

Sigfox

Criterion for determining suitability	Score
Suitability of the frequency band (KO criterion) Unnecessarily high data transmission rate and excessive range; therefore, excessive sensor energy consumption. High latency times. Limited transmitting capacity.	Low (0 points)
Manufacturer dependence No standardized protocol. All devices use single-source IC components. Provider dependency.	High (0 points)
Infrastructure No own infrastructure necessary, service provider infrastructure available.	No own infrastructure (2 points)
Integrability Integration of sensor data with building automation controllers (DDC systems) is only possible via an IP-based network (no direct connection possible).	Middle (1 point)
Market availability Sensors for building automation applications are not available at present.	Low (0 points)
Measuring & testing Measuring & testing equipment is available, but complicated to use.	Middle (1 point)
Power supply Mains power, or battery-powered sensors.	Battery-powered (1 point)
Data encryption Data security solutions available.	High (2 points)

Overall assessment At present, unsuitable for building automation applications due to frequency band characteristics.	**Low (KO criterion)**

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Thread	
Criterion for determining suitability	**Score**
Suitability of the frequency band (KO criterion) Data transmission rate, range and latency time within the required range. Critical energy consumption due to high transmitting power in the 2.4 GHz frequency band, especially with mesh structures.	Middle (1 point)
Manufacturer dependence Standardized protocol.	Low (2 points)
Infrastructure Integration of sensor data requires an own infrastructure. Mesh technology can help to lower costs.	Infrastructure/ Mesh (1 point)
Integrability Integration of sensor data with building automation controllers (DDC systems) is only possible via an IP-based network (no direct connection possible).	Middle (1 point)
Market availability Limited device availability for building automation applications.	Low (0 points)
Measuring & testing Dedicated equipment is not available. Measuring & testing require cable-based connection to wireless interfaces.	Middle (1 point)
Power supply Mains power, or battery-powered sensors.	Battery- powered (1 point)
Data encryption Data security solutions available.	High (2 points)

Overall assessment Essentially suitable for building automation applications. However, reduced availability of measuring & testing equipment and the lack of direct integrability, as well as reduced market availability of the necessary components and the lack of self-powered sensor technology, represent major deficits.	**Middle** (Ø 1.1 points)

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WLAN	
Criterion for determining suitability	**Score**
Suitability of the frequency band (KO criterion) Unnecessarily high data transmission rate; therefore, excessive sensor energy consumption. Critical energy consumption due to high transmitting power in the 2.4 GHz frequency band.	Low (0 points)
Manufacturer dependence Standardized protocol.	Low (2 points)
Infrastructure Backbone infrastructure required for integration of sensor data.	Infrastructure/ Mesh (1 point)
Integrability Integration of sensor data with building automation controllers (DDC systems) is only possible via an IP-based network (no direct connection possible).	Middle (1 point)
Market availability Limited device availability for building automation applications.	Low (0 points)
Measuring & testing Dedicated equipment, plus the relative user documentation, is available and easy to use.	High (2 points)
Power supply Mains power, or battery-powered sensors.	Battery- powered (1 point)
Data encryption Data security solutions available.	High (2 points)

Overall assessment At present, unsuitable for building automation applications due to frequency band characteristics.	**Low (KO criterion)**

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ZigBee / ZGP	
Criterion for determining suitability	**Score**
Suitability of the frequency band (KO criterion) Data transmission rate, range and latency time within the required range.	High (2 points)
Manufacturer dependence Partly standardized protocol. Manufacturer-specific implementation; low interoperability.	Middle (1 point)
Infrastructure Integration of sensor data requires an own infrastructure. Mesh technology can help to lower costs.	Infrastructure/ Mesh (1 point)
Integrability Integration of sensor data with building automation controllers (DDC systems) is only possible via an IP-based network (no direct connection possible).	Middle (1 point)
Market availability Limited device availability for building automation applications.	Middle (1 point)
Measuring & testing Dedicated equipment, plus the relative user documentation, is available and easy to use.	High (2 points)
Power supply Mains power, or battery-powered sensors. Energy Harvesting for some devices (self-powered).	Battery- powered (1 point)
Data encryption Data security solutions available. Past data security issues resolved with current Version 3.0.	High (2 points)

Overall assessment	
Overall assessment Essentially suitable for building automation applications. However, manufacturer-specific implementation (i.e. manufacturer dependence) and the lack of direct integrability, as well as reduced market availability of the necessary components, represent major deficits.	**Middle** (Ø 1.4 points)

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Z-Wave

Criterion for determining suitability	Score
Suitability of the frequency band (KO criterion) Data transmission rate, range and latency time within the required range.	High (2 points)
Manufacturer dependence Manufacturer-specific standardized protocol. Varying implementation; low interoperability.	Middle (1 point)
Infrastructure Integration of sensor data requires an own infrastructure. Mesh technology can help to lower costs.	Infrastructure/ Mesh (1 point)
Integrability Integration of sensor data with building automation controllers (DDC systems) is only possible via an IP-based network (no direct connection possible).	Middle (1 point)
Market availability A broad range of sensors for building automation automation applications is available.	High (2 points)
Measuring & testing Dedicated equipment, plus the relative user documentation, is available and easy to use.	High (2 points)
Power supply Mains power, or battery-powered sensors.	Battery-powered (1 point)
Data encryption Data security solutions available.	High (2 points)

Overall assessment Essentially suitable for building automation applications. However, varying implementation (i.e. manufacturer dependence) and the lack of direct integrability, as well as the lack of self-powered sensor technology, represent major deficits.	**High** (Ø 1.5 points)

5.2 Overview of findings

Criterion	5G	BLE	EnOcean	KNX RF	LoRa	NB-IoT	Sigfox	Thread	WLAN	ZigBee	Z-Wave
Suitability of the frequency band (KO	Low	High	High	High	Low	Low	Low	Middle	Low	High	High
Manufacturer dependence	Middle	Middle	Low	Low	High	Middle	High	Low	Low	Middle	Middle
Infrastructure	No own Infra-structure	Infra-structure	Infra-structure	Infra-structure	Infra-structure	No own Infra-structure	No own Infra-structure	Infra-structure/Mesh	Infra-structure/Mesh	Infra-structure/Mesh	Infra-structure/Mesh
Integrability	Middle	Middle	High	Middle	Middle	Middle	Middle	Middle	Middle	Middle	Middle
Avaiability of hardware comp.	Low	Middle	High	Middle	Low	Low	Low	Low	Low	Middle	High
Measuring and testing	Middle	High	High	Middle	Middle	Middle	Middle	Middle	High	High	High
Power supply	Battery	Battey	Self-powered	Battery	Battery	Battery	Battery	Battery	Battery	Battery	Battery
Data encryption	High	High	High	High	High	High	High	High	High	High	High
Overall suitability	Low (KO-Crit.)	Middle (Ø 1.4 Pt)	High (Ø 1.9 Pt)	Middle (Ø 1.4 Pt)	Low (KO-Crit.)	Low (KO-Crit.)	Low (KO-Crit.)	Middle (Ø 1.1 Pt)	Low (KO-Crit.)	Middle (Ø 1.4 Pt)	High (Ø 1.5 Pt)

6   Conclusions

Various wireless standards are available for building automation applications. The most suitable wireless technology can only be identified, case by case, according to the „use cases".

In this context it has become apparent that the so-called „Wide Area Networks" are unsuitable for today's and tomorrow's Smart Building applications. This technology is well suited to integrating wireless devices into public areas, i.e. where it is impossible to establish one's own infrastructure. In modern buildings, however, setting up an own infrastructure or establishing mesh networks presents no problems and makes excellent sense in consideration of the density of the sensor networks.

Other wireless technologies are more - or less - suited to this kind of application. The possibility of integrating wireless devices (especially sensors) into building automation systems - e.g. controllers and DDC-systems - is of particular relevance. The support for specific wireless tecnologies offered by controller manufacturers plays an important role. As does the possibility of sourcing a broad range of compatible components on the open market. Not to mention the great advantages offered by self-powered wireless devices requiring neither batteries nor mains power.

From these points of view, the EnOcean and Z-Wave wireless standards appear to be ideal for use in „Smart Buildings". EnOcean achieved a mean score of 1.9 points on the suitability index followed by Z-Wave with 1.5 points.

However, these technologies cater for different market segments. EnOcean is predestined for use in professionally-installed integrated systems for Smart Home and non-residential building solutions and features higher levels of interoperability. In contrast, Z-Wave is better suited to „DIY" Smart Home consumer-level retrofit applications.

7   Sources

Abbreviation	Source
[AN1141]	AN1141: Thread Mesh Network Performance; Silicon Labs; 2019
[Becker 2007]	Energieeffizienz durch Einsatz von Raum- und Gebäudeautomation mit Bezug zur DIN V 18599 und EN 15232, Martin Becker; Vortrag zur GLT Anwendertagung; 2007
[de 2012]	Aufbau, Test und Optimierung einer Funkverbindung; dresden elektronik; 2012
[EN15232 2017]	DIN EN 15232-1 Energieeffizienz von Gebäuden; Beuth Verlag GmbH; 2017
[EnO 2019]	EnOcean Serial Protocol 3 (ESP3); EnOcean GmbH; 2019
[EnO 2020]	https://www.enocean-alliance.org/de/; EnOcean Alliance; 2020
[Hüttemann 2020]	Trends von Raumautomation und Building Management Systemen in modernen Bürogebäuden; Dominik Hüttemann; 2020
[IGT 2015]	Fragebogen „Planungsprozess Smart Home & Smart Office"; Institut für Gebäudetechnologie; 2015
[IGT 2019]	Planungsprozess(BMS-IoT)-Checkliste, Institut für Gebäudetechnologie; 2019
[InfoTip 2020]	Bluetooth Kompendium; InfoTip Service GmbH (https://kompendium.infotip.de/bluetooth.html); 2020
[Kabitzsch 2015]	Drahtlose und Drahtgebundene Sensor-Aktor-Netzwerke; Prof. Klaus Kabitzsch; TU Dresden; 2015
[KNX 2013]	Grundlagen zum KNX Standard; KNX Organisation; 2013
[KNX 2015]	Systemdokumentation KNX RF; Giersiepen GmbH & Co. KG; 2015
[LoRa 2020]	https://lora-alliance.org/; LoRa Alliance; 2020
[Pätz 2017]	Dr. Christian Pätz; Z-Wave: Die Funktechnologie für das Smart Home; 2017
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