Journal of
Low Power Electronics and Applications

MDPI

Review

A Survey of Short-Range Wireless Communication for Ultra-Low-Power Embedded Systems

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Abstract: Wireless short-range communication has become widespread in the modern era, partly due to the advancement of the Internet of Things (IoT) and smart technology. This technology is now utilized in various sectors, including lighting, medical, and industrial applications. This article aims to examine the historical, present, and forthcoming advancements in wireless short-range communication. Additionally, the review will analyze the modifications made to communication protocols, such as Bluetooth, RFID and NFC, in order to better accommodate modern applications. Batteryless technology, particularly batteryless NFC, is an emerging development in short-range wireless communication that combines power and data transmission into a single carrier. This modification will significantly influence the trajectory of short-range communication and its applications. The foundation of most low-power, short-range communication applications relies on an ultra-low-power microcontroller. Therefore, this study will encompass an analysis of ultra-low-power microcontrollers and an investigation into the potential limitations they might encounter in the future. In addition to offering a thorough examination of current Wireless short-range communication, this article will also attempt to forecast future patterns and identify possible obstacles that future research may address.

Keywords: NFC (near field communication); RFID; ultra-low-power microcontroller; batteryless; Bluetooth; Wi-Fi; short-range communication; wireless communication

Citation: Baker, B.; Woods, J.; Reed, M.J.; Afford, M. A Survey of Short-Range Wireless Communication for Ultra-Low-Power Embedded Systems. *J. Low Power Electron. Appl.* **2024**, *14*, 27. https://doi.org/10.3390/jlpea14020027

Academic Editor: Orazio Aiello

Received: 11 March 2024
Revised: 2 May 2024
Accepted: 9 May 2024
Published: 14 May 2024

1. Introduction

Short-range wireless technology is a vital part of modern life, with its reach continuing to grow [1]. It is used in most sectors, from wireless payments in shops and door access in schools [2] to TV remotes at home. Its continued growth has been powered by the widespread use of smartphones, which are ubiquitous in the modern era, reaching above 80% ownership in Germany, the UK and the USA [3] and 4.6 billion smartphone users worldwide in 2023 [4], bringing short-range wireless technology to the forefront of applications.

This review paper will cover a brief history of short-range wireless technology, an in-depth review of modern low-power applications using short-range wireless technology, as well as predictions of the future of short-range wireless technology and the research that is needed to improve or adjust short-range wireless technology for future applications. Short-range wireless communication is an extensive term that can be split into two parts: *wireless* can be defined as a gap between the transmitter and receiver that is not connected by wires, while *short range* changes depending on the use case and protocol—in this article, short range will be any protocol with a typical range below 100 meters; communication means data are at least transmitted from one system to another system. This defines the minimum requirements for a protocol to consist of short-range wireless communication in this article.

Understanding whether a short-range wireless system is passive or active is crucial in grasping its use cases and applications. Active refers to a state where both sides of the overall system are simultaneously powered, whereas passive indicates a condition where only one side is powered i.e., the opposite side receives power through the transmission. An example of an active system is a TV remote. The TV remote operates using a battery, while the TV itself is powered by the mains supply, ensuring that both the transmitter and receiver are supplied with power. An instance of a passive system would be wireless payments, such as credit cards. In this instance, the credit card receives power via inductive coupling from the RFID reader, indicating that it is a passive system, as one side is not powered by an internal power supply.

Table 1 displayed above shows the most prevalent short-range wireless technologies, with the range indicating the highest rated distance of their typical application. A non-line of sight protocol refers to a situation where the signal has the ability to pass through the outer covering of an electromagnetically permeable case, e.g., plastic. This is essential for embedded systems where direct visibility between the transmitter and receiver is usually unattainable. A Broadcast technology allows the transmitter to natively communicate with multiple devices at the same time. Each short-range technology serves different purposes but can generally be categorized into two primary applications, identification and data transfer, with specific technologies capable of performing both functions. Identification methods include UWB, barcode, UHF RFID, VHF RFID, and HF RFID. Data transfer can be achieved through various means, including infra-red communication, Wi-Fi, Bluetooth, and NFC.

Table 1. Table comparing short-range technology.

Name	Passive/Active	Range in Meters (m)	Non-Line of Sight	Broadcast	Identification/Data Transfer
Optical communications [5]	Active	7 m	NO	NO	Data transfer
VHF and HF RFID [6]	Passive	0.1 m	YES	YES	Identification
UHF RFID [7]	Passive/Active	1 m/100 m	YES	YES	Identification
NFC [8]	Passive/Active	0.1 m	YES	NO	Data transfer
Barcode [9]	Passive	0.1 m	NO	NO	Identification
Wi-Fi [10]	Active	≥10 m	YES	YES	Data transfer
Bluetooth [11]	Active	5 m	YES	NO	Data transfer
UWB [12]	Active	15 m	YES	YES	Data transfer
MST * [13]	Passive	0.1 m	YES	NO	Identification

* Magnetic Secure Transmission.

Various constraints exist for each of the short-range technologies, encompassing factors such as costs, availability, and power consumption. The method of communication varies depending on the specific application or circumstance. Nevertheless, there are instances where certain short-range technologies are becoming obsolete and surpassed in particular functions due to overlaps, such as infra-red communication being substituted by Bluetooth and Wi-Fi and Magnetic Secure Transmission being replaced by NFC. However, certain technologies persist in usage despite the availability of alternative options that excel in specific domains, such as substituting barcodes with RFID tags. The implementation of this latter technology is generally limited to industrial applications rather than retail applications, primarily due to its higher cost.

Short-range wireless technologies such as Wi-Fi (IEEE 802.11 Wi-Fi standards) and NFC are constantly evolving, with new revisions being released on a regular basis. For instance [14], Wi-Fi 6 (802.11ax) was released in 2019, and RFID ISO/IEC was revised in 2020. The reason behind these constant revisions is the evolution of parallel technology and its applications. For instance, NFC technology is now a standard feature in most modern smartphones. However, it was introduced in 2004 and was developed in anticipation of the growing popularity of mobile phones [15]. Similarly, low-power embedded systems currently use Bluetooth mesh and dynamic NFC technology. However, they may evolve to adapt to ultra-low-power or batteryless applications in the future. It is evident that NFC, UHF, HF, and VHF RFID are interlinked. NFC, also known as Near Field Communication, can be regarded as a derivative of RFID technology. This communication protocol operates at a frequency of 13.56 MHz and shares protocols with HF RFID (ISO14443 [16] and ISO15963 [17]). However, NFC has distinct features and use cases compared to RFID. One notable difference is that some NFC devices can switch between tag and reader modes, enabling two-way data transfer. Additionally, NFC is limited to Peer-to-Peer communication, whereas RFID may transmit in broadcast mode. There are multiple different frequencies used for RFID technology: 125 KHz (VHF), 13.56 MHz (HF), 433 MHz (Active UHF), and 865–915 MHz (Passive UHF). Each frequency serves a specific purpose. The 125 kHz (VHF) and 13.56 MHz (HF) frequencies operate through inductive coupling. The 433 MHz (Active UHF) and 2.45 GHz (Active Microwave) frequencies are used for active tags, which means they require a battery but have an enhanced transmission range. On the other hand, the 865–915 MHz (Passive UHF) frequency utilizes backscatter to transmit data.

While identification is the basis for many protocols and applications, data transfer can also achieve identification while also having unique communication applications. Data transfer is typically dynamic, while identification is static. Dynamic means that both sides of the system are active, and so for data transfer to occur, both sides must communicate with each other. While communication is the normal focus of short-range wireless technology, there is another area, short-range energy harvesting technology, which transmits power between devices instead of data. An example is wireless power transfer [16], which can be included in wearable devices or electric vehicles. Wireless power transfer typically uses inductive coupling to transmit power between devices.

Another crucial area is the network type of the protocol [17]. A Personal Area Network (PAN) is used for connecting devices within a small area, typically within a range of less than 10 meters. A local area network (LAN), on the other hand, is used to connect devices within a wider location such as a building, office or home. A LAN is normally less than 100 meters. Lastly, a wide area network WAN is used to connect devices over a larger area, including a metropolitan area and international connections. PAN examples include the majority of short-range wireless protocols such as Bluetooth and infra-red connections. However, Wi-Fi is an example of a LAN network. WAN technologies are not typically used in short-range networks.

The rest of this paper is organized as follows: Section 2 will review a brief history of short-range technology and give a timeline of major developments. Section 3 will cover four of the most used short-range protocols: Bluetooth, Wi-Fi, UWB, and RFID. Section 4 will go into detail about the developing technology of batteryless communication, which, as introduced before, combines both communication and power transmission. Section 5 covers an overview of the power consumption of short-range wireless communication applications. As will be discussed in Section 5, a critical factor of the majority of low-power embedded applications is the microprocessor, so Section 6 will review current ultra-low-power microcontrollers and their future limits, as ultra-low-power microcontrollers are the key limiting factor to making ultra-low-power applications feasible. Section 7 discusses the future of short-range wireless protocols and applications before concluding in Section 8.

2. Brief History of the Evolution of Wireless Short-Range Technology

Short-range wireless communication did started gaining traction after 1945. Before 1945, there were some short-range wireless technologies; however, their use cases were minimal, and wired communication was used for most purposes. That changed in a unique case of international espionage: the "Great Seal Bug" [18] in 1945 was one of the first passive short-range communication devices to be used in a real-world application. The device was powered externally by a transmitter and covertly transmitted audio. "The Great Seal Bug" [18] is the precursor to modern RFID. The espionage device shows the possibility of transferring data passively, and the possibilities of the technology have become apparent in the modern era with the invention of standard RFID.

Before 1980, the widespread use of short-range wireless technology was limited. In the 1960s and 1970s, research into short-range communication was ongoing and with real-world technology bringing more commercial products such as TVs into households, wireless communication between two devices became a necessity. The first TV remote invented in the 1940–1950s used light to send signals; however, in the 1960s, ultrasonic TV remotes were introduced. While infra-red TV remotes were developed in 1970, they were not used in commercial products until the 1980s. The introduction and innovation of new technology were due to the increase in real-world applications in the case discussed due to the proliferation of the TV; however, this revolution also happened in many sectors and products.

The decades between 1980 and 2000 saw the rapid advancement of RFID. Both passive and active RFID became commercially available, with one of the active main uses being animal tracking with the introduction of ISO 11784 in 1994, while passive RFID became a mainstay in libraries and shops. This has become possible because of low-voltage, low-power CMOS logic circuits. The technology of low-voltage, low-power CMOS logic circuits made passive RFID possible, causing a surge in use. In 1985, an RFID tag circuit would cover 1/4 of a credit card [6], while by 1999, an RFID circuit could be built into a single IC, significantly reducing the size. The massive reduction in cost and size between 1980 and 2000 has led to the modern adoption of RFID. What can be gathered from the development of RFID is that hardware improvements influence the applications of the protocol, so while there is no direct change in the protocol, ongoing research and development will cause changes in the applications and use cases.

Bluetooth first standard was released in 1999 [19]; however, since then, there has been substantial modification to the Bluetooth protocol, which was made for computer peripherals. The modifications have led to a standard that works specifically with battery and IoT devices; this can be seen in Bluetooth version 4, which lowered energy consumption (Bluetooth low energy (BLE)), making the protocol more efficient for IoT applications.

In [20], published in 2007, it states, "RFID finds relatively limited applications these days and must overcome many technical hurdles for wide acceptance. However, none of these hurdles seems to pose a fundamental barrier, and it is evident RFID will soon be pervasive in our daily life". While UHF RFID has not replaced bar-codes in low-cost environments, it has increased use in smart factory concepts [21]; it has also been looked at as a batteryless solution with ideas such as WISP and UHF RFID sensors. HF RFID (ISO14443 and ISO15963) has been used as a standard for NFC.

The increase in low-power battery devices in the mid/late 2000s influenced the creation of the NFC forum and publication of ISO 18000-3 [22] in 2004; the development of BLE in 2010; and the publishing of Zigbee (802.15.4) in 2003 [23]. The adoption of new or adapted protocols started around 2005, with the main use case being low-power, battery-powered embedded systems. The shift to battery-powered, wireless connected devices has enabled greater convenience, mobility, and connectivity in various aspects of the modern era, from smartphones and wearables to smart homes and the Internet of Things (IoT) [24].

If the timeline is to be defined, the development of data transfer short-range protocols spans two different eras: the current battery-powered era, and the era before battery-powered devices became dominant, which was the mains-powered era. The battery era heavily influenced short-range communication protocols which were modified and created to focus on low-power battery-powered systems. This came with different specifications to the prior era of short-range communication, which was made for either mains-powered to mains-powered communication or mains-to-battery systems. The main difference between the two eras is that low-power communication was a necessity in battery-powered devices, which has caused a shift in short-range wireless communication protocols. This shift has caused the development and modification of protocols to fit the low-power application, protocols such as Bluetooth low power (BLE) and Zigbee.

3. Overview of Modern Day Short-Range Wireless Communication Protocol

3.1. Comparing Modern-Era Short-Range Wireless Protocols

The volume of research related to each communication protocol is hard to measure; however, Table 2 shows the number of journal entries based on the keyword between the years 2018 and 2024. These data show that the most researched protocol is RFID, followed by Bluetooth and Wi-Fi; however, this only gives a brief overview of the influence of certain protocols in the research. Figure 1 displays the grouping of different frequency bands; a protocol's frequency is a critical factor. The most popular band is the 2.45 GHz band with Bluetooth, Wi-Fi, and Zigbee; it contains two of the dominant protocols as seen in Table 2. Ultra-wideband differs from the others in both the frequency range and its application, which is mostly for localization rather than data transmission.

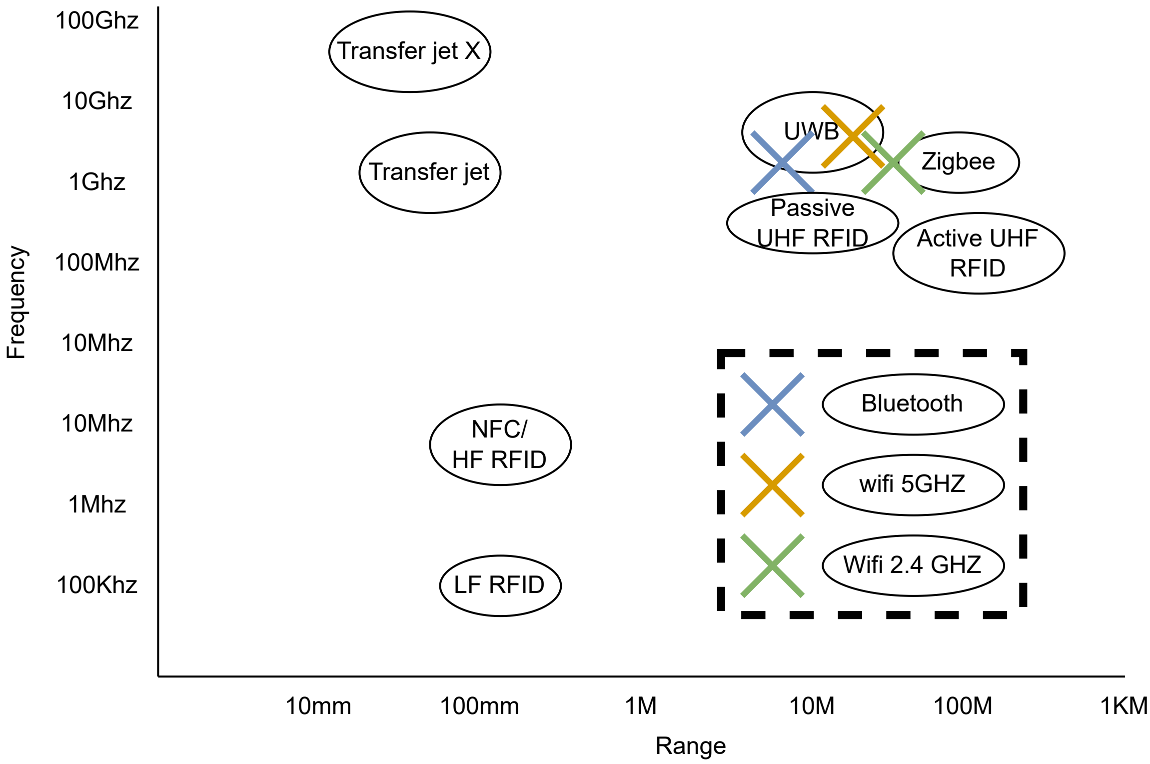

Figure 1. Graph of short-range protocols.

Table 2. Table of IEEE journal entries for keyword 2018–2024.

Keyword	Search Results
RFID	2627
BLUETOOTH	1723
Wi-Fi	1328
UWB	1152
QR	794
UHF RFID	402
NFC	130
BARCODE	98

3.2. RFID

RFID Types

RFID is split into a range of different frequencies; however, there are two main components to every RFID system: readers and tags. All RFID readers transmit data that is modulated by an RFID tag. There are two main methods of communication through RFID depending on the frequency used as seen in Table 3 *near field inductive coupling* or *backscatter coupling*. Near field coupling is used by LF and HF RFID due to the longer wavelength [25].

Table 3. Table comparing RFID technology.

Name	**Low-Frequency RFID**	**High-Frequency RFID**	**Active UHF RFID**	**Passive UHF RFID**	**Microwave RFID**
Frequency	125/134 KHz	13.56 MHz	433 MHz	860–928 Mhz	2.45 GHz/5.8 GHz
Typical Type	Passive	Passive/Active	Active	Passive	Passive/Active
Read range	0.3 m	1 m	100 m	6 m	10 m
Dipole Antenna size	1141.2 m	10.52 m	329.45 mm	155.9 mm	58.22 mm
Communication method	Near field inductive coupling	Near field inductive coupling	Transmitter Backscatter coupling	Backscatter coupling	Backscatter coupling

A system is said to be in near field at a distance of $C/2\pi f$ where C is the speed of electromagnetic radiation and f is frequency. Thus, using the relevant frequencies, we can define this for the relevant bands as:

$$\text{LF RFID:}\quad 3 \times 10^8/(2\pi \times 125 \times 10^3) = 382\text{ m}$$

$$\text{HF RFID:}\quad 3 \times 10^8/(2\pi \times 13.56 \times 10^6) = 3.52\text{ m}$$

$$\text{UHF RFID:}\quad 3 \times 10^8/(2\pi \times 860 \times 10^6) = 0.055\text{ m}$$

As can be seen, the near field region will only work with LF and HF RFID tags as the near field region drops below 10 cm at UHF, so UHF and microwave RFID use Far Field coupling. At these higher frequencies, a technique called backscatter [20] is used to reflect the electromagnetic wave.

RFID was developed for identification and detection. Detection that an RFID tag is in the range of the RFID reader is a main feature of RFID. This is the type of system used in many retail outlets for device detection. While the retail outlet scenario is interesting, most do not have a smart system, so it only detects when a tag is in the range of the sensor and not the specific tag. This is where the libraries use case [26] is unique; they use both parts of RFID identification and detection in one system. This system means a book can be tracked around the library in the same way RFID is used in logistics and can be sorted using its ID and then placed either by hand or by conveyor to the correct location. It was also used to know when a nook had left the library. This can be performed by an allowlist to only let certain IDs through the RFID reader.

Some RFID detection systems are used to track people. For example, an RFID tag is applied to clothing such as boots [22]. This smart system can detect how often the RFID tag is moved through the reader. Alternative methods use wristbands, which can be seen at major attractions; this uses a handheld reader to scan the RFID tag.

RFID has many applications, with identification being the most prominent use case. It is widely used in industries such as retail, logistics, healthcare, and asset tracking. While RFID is used in regular identification systems, such as logistics and asset tracking, there is another use case where RFID is used as a sensor. This significantly changes the use cases of RFID and has the potential to use RFID as the communication protocol to obtain a low-power passive sensor, which, in some research, is a batteryless system. Unlike the typical RFID use for identification and detection, where RFID tags are detected by RFID readers, RFID as a communication protocol for low-power passive sensors involves using RFID technology to transmit data from the sensor to a reader. This means that the RFID tag itself acts as a sensor, collecting and transmitting data such as temperature, humidity, or pressure [27]. This opens up new possibilities for applications where battery-powered or wired sensors are not feasible or practical. However, there are many different methods for RFID sensors. The three main categories of sensors are battery-assisted RFID sensors, hybrid RFID sensors, and batteryless RFID sensors. There are two main methods for RFID sensors: chipless and chip-based.

Chip vs. chipless systems: As stated, these are the two main design methods. One is centered around using a solution-on-chip to perform communication. While chipless systems [28] use many different types of communication techniques, some examples are On–Off Keying (OOK), Pulse Position Modulation, Phase Modulation and Backscattered-Based Tags. On–Off Keying tags transmit using 1 or 0, so one way to perform this technique is to use a capacitor [29] to detect when the transmission should be reflected back to the reader. This is a simple way to obtain a binary sensor. Pulse Position Modulation uses the same binary signals with 1 and 0; however, it changes the signal based on a timing window if, with a 0 and 1 reflection timing transmitting a 0 or 1 [30], Phase Modulation uses a number of [31] delay lines to effect the phase of the signal with the number of delay lines being proportional to the number of bits. Backscattered-Based Tags [32], instead of using the time domain, use the frequency domain and so the tag can change its resonance frequency and so can be different from other tags with the same use case as barcodes, a cheap solution to identify products.

Battery-assisted RFID sensors, as the name implies, use a battery and, therefore, an active tag; however, for RFID sensors, most research uses the passive range for these sensors. This is due to the different use cases for UHF active RFID at 433 MHz, which is most commonly used for long-range identification or tracking. At the same time, RFID sensors do not have a range at the forefront of their application; the battery's main purpose is to collect data and then use passive RFID to transmit data, saving power and conserving lifespan. This idea also has the difference that, in some scenarios, the battery can be charged through RF energy harvesting, meaning a smaller battery or supercapacitor can be used, and the tag can be smaller and be embedded for years and could theoretically have an indefinite lifespan if powered periodically [33].

Batteryless RFID sensors have no battery, which significantly changes the dynamics of the tag, as it is a passive tag with active features. It uses a low-power sensor to gather data and uses backscatter to send the signal. The WISP Wireless Identification and Sensing Platform [34] is one of the design ideas for a batteryless RFID. This specifies the use of an ultra-low-power microcontroller, which makes it flexible enough to be used with many different sensors, and this would lead to many applications, such as temperature sensing. There are many different types of batteryless RFID designs, and [35] Chipless, Antenna Resonance, Multi-Port Architecture, and Digitally Integrated are four different types of batteryless RFID sensor methods.

Hybrid RFID systems can be either batteryless or battery-assisted RFID sensors; however, they are normally associated with battery-assisted RFID. This can be split into a communication or power hybrid system. A communication-hybrid system uses another short-range communication technology to transfer data; Bluetooth [36] can be paired with either RFID or Zigbee [37], RFID can be used for location-based sensing while Zigbee can communicate at extended distances, making a system that can be used for message-based detection when an object reaches a selected location. Energy harvesting and RFID are the main use cases of hybrid RFID. This type of RFID uses extremely low power transmission with an alternate energy source, which can be RF, solar, or piezoelectric energy harvesting.

RFID is a growing sector of research [38], with the increase starting around 2010 with the advent of the Internet of Things (IoT) and the adoption of other short-range communication, such as Bluetooth BLE, making wireless handheld portable systems inexpensive. RFID is also the most common protocol term since 2018 in the keyword search shown in Table 2, which shows that research into RFID development is continuing in the modern era.

3.3. Bluetooth Low Power Applications

Bluetooth has been in development since 1999 when Bluetooth version 1 was introduced; however, a major development occurred in 2010 when Bluetooth 4 was introduced, bringing Bluetooth low energy (BLE). This created a shift in the Bluetooth protocol and its applications, with Bluetooth inclusion in a growing number of devices. There were 2.7 billion device shipments that included Bluetooth in 2014; in 2023, it was estimated that there would be 5.4 billion [39], with the growth of Bluetooth devices continuing into the future [19]. As mentioned, BLE is a subset of Bluetooth and is specifically made for low-power battery-powered devices and IoT. Its main difference from Bluetooth is its work cycle, while Classic Bluetooth is always paired. BLE can go into sleep mode and has a protocol stack specifically built for low power, which drastically reduces power consumption while also being built to be connected to unlimited devices. Classic Bluetooth only has a limit of eight simultaneous devices.

Due to its work cycle nature, BLE has unique applications in sensor networks and IoT, which include fields such as logistics, retail, and medical. The sleep cycle of the BLE device is a critical factor; ref. [40] shows that a round trip with a connection interval of 375 ms has an estimated lifespan of 2 years, while a connection interval of 4000 ms has a lifespan of 12 years using a CC2540 (SoC) for Bluetooth low-energy applications [40]. The power consumption ranges from 10 mA at 7.5 ms intervals to less than 100 µA at 375 ms. This does not take into account the sensing power and the ultra-low-power microcontroller work cycle, which shows the possibility of BLE low-power sensors and applications [41].

BLE has many applications in the medical field; for example, [42] describes a sensor for blood pressure monitoring using a CC2541F256 SoC. It combines the BLE RF transceiver and an 8051 MCU, with the reader of the sensor being a smartphone with a custom app. This is a typical BLE sensor design with the sensor being powered by a battery. The work by Lin et al. shows a complete platform for BLE in the medical use case [43]; in this IoT solution, the sensor is connected to the cloud as shown in Figure 2. This means data can be collected from a sensor network and accumulated in an online database. These applications can be used to monitor people consistently and without the need for an on-site visit in some circumstances. The issue with this system is that it needs two protocols, BLE and Wi-Fi, to be compatible, and so it has three points of failure: a sensor, a smartphone, and Wi-Fi.

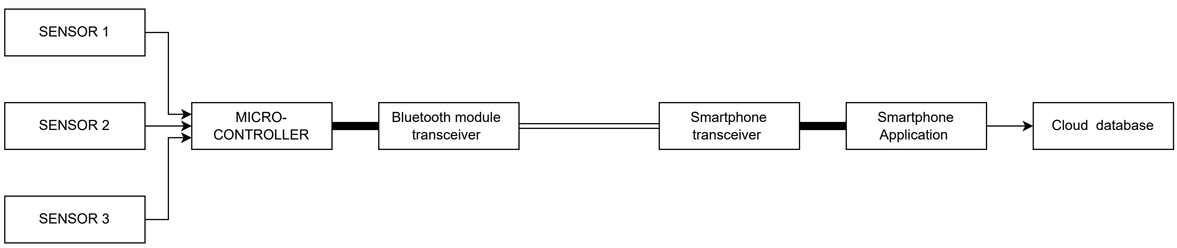

Figure 2. Bluetooth sensor network block diagram.

BLE has a major advantage in hybrid systems, as its work cycling transmission means it has low power, compared to an alternative such as Wi-Fi; extended range, compared to NFC; and compatibility with smartphones, compared to UHF RFID. A hybrid system has distinct advantages [44]. For example, combining BLE and Wi-Fi makes a distinct hybrid system, with BLE low-power sensors data can be collected and then through Wi-Fi they can be stored in the cloud. However, this also means updates can be sent as well to multiple sensors. This hybrid functionality can also be included into a single SoC such as the ESP32 and ESP8266 devices, which have both BLE and Wi-Fi capabilities. An indoor localizing system can be the combination of Wi-Fi and Bluetooth [45], showing that combining the two technologies in parallel is also an alternative, giving more reading and better reliability.

The other hybrid BLE design combines BLE and energy harvesting. This can be performed with different energy-harvesting methods; however, due to the higher power consumption of BLE compared with RFID, the most viable option for energy harvesting is solar [46]. There are a number of commercial BLE hybrid systems available, such as Cyalkit-E02 BLE beacon and Gimbal BLE beacon. These show the viability of BLE and solar hybrid technology with a power consumption of 0.17 mW and 0.28 mW, respectively, with a range of 0.59 m and 0.31 m. They are low-power, low-range technologies that can be powered by a solar cell measuring 15 mm × 15 mm [47].

3.4. Wi-Fi Low Power Applications

Wi-Fi has many versions and is defined in IEEE 802.11 [48]. The 802.11b (2.4 GHz signaling) is the original 1999 standard, and 802.11g was released in 2003; both are 2.4 GHz Wi-Fi versions. Ultra-low-power Wi-Fi suggests a similar idea to BLE, which changes the work cycle from a 100% work to a sleep/wake-up cycle doing the same; this means performing bursts of work and then sleeping until the next transmission. An example of limiting Wi-Fi to reduce power consumption is limiting packets per second. The transmission of 10 packets per second with a battery of 7500 mAH would last approximately 40 months, while increasing the packets per second to 100 packets per second would make the battery life decrease to 20 months and another increase to 330 packets would only last 10 months, respectively [49].

Wi-Fi [50] is used in IoT to link PAN and LAN networks to a database; this is a critical infrastructure in IoT applications. Some IoT applications that contain Wi-Fi have the prospect to be used in a smart grid, intelligent environment protection, and precision agriculture [51]. An ESP8266 is a module with Wi-Fi standard IEEE 802.11 b/g/n, and with a 1000 mAh battery can last 40–60 h in light sleep [52], depending on the transmission interval. Wi-Fi also has a use case in tracking and identification, while this is not its main use case [53]. Research into Wi-Fi-based localization has been performed and is viable. This brings up the comparison to RFID. While Wi-Fi transmitters are cheaper and have a longer range than RFID transmitters, RFID transmitters have significantly lower power due to backscatter as well as having significantly reduced cost per device.

Another interesting use case of Wi-Fi is in energy harvesting; compared to RFID or BLE, where the energy harvesting is received, Wi-Fi could act as a transmitter for RF energy harvesting, which could power an ultra-low-power sensor in an indoor environment. There has been research on Wi-Fi energy harvesting [54]; however, the issue is the efficiency of energy harvesting with multiple antennas having an efficiency below 20% and a maximum output of 2V at 1mA output. Another area of research is hybrid Wi-Fi systems; this could be with another LAN protocol such as LIFI [55] or a PAN protocol [56] such as Bluetooth.

3.5. Ultra Wide Band (UWB) Short-Range Applications

Ultra-WideBand (UWB) is defined in IEEE 802.15.4, and the primary use case is location-based sensing, specifically, the time of flight sensing. The first standard was released in 2007 (IEEE 802.15.4a) [12]. UWB spans from 3.1 to 10.6 GHz. However, different global regions have varying UWB-allocated frequencies.

One of the main differentiation factors between UWB and other wireless short-range communication methods is the frequency band as indicated in the name. There are 16 predefined channels, with channels 1–16 ranging from a center frequency of 3494.4 MHz and channel 16 having a center frequency of 9484.8 MHz [12]. Compared to other protocols, UWB has less traffic at its designated frequency as seen by Figure 1, and UWB signals employ a significantly wider bandwidth than other technologies such as Wi-Fi and Zigbee. This wider bandwidth means a shorter pulse is needed for communication.

One of the applications for Hybrid UWB entails integrating UWB with alternative short-range wireless communication protocols, including Bluetooth low energy (BLE) [57], Wi-Fi [58], or UHF RFID [59]. By means of this integration, UWB hybrid systems are able to exploit precise positioning and high data transfer rates while benefiting from low power consumption compared to BLE and Wi-Fi due to their shorter duty cycle.

An instance of this can be seen in a hybrid UWB and BLE system, where UWB is employed to facilitate precise indoor positioning and proximity detection; this hybrid technology can also be combined with Wi-Fi for a flexible system [60], and BLE serves as a low-power conduit for transmitting data over greater distances or establishing connections with devices lacking UWB support. Short-range precision tracking accuracy and long-range data transfer are essential for applications such as asset tracking, indoor navigation, and smart home automation; hybrid UWB can be a feasible solution.

Overall, UWB communication offers high data transfer rates, precise positioning capabilities, resistance to interference, and ultra-low average power consumption, making it well suited for a wide range of applications across industries and applications that require identification and tracing capabilities.

4. In-Depth Discussion of Batteryless Near Field Communication (NFC)

NFC is based on RFID protocols ISO 14443 and ISO 15963 [61] and has five tag types. Type 1–4 use ISO 14443 and have a range of 100 mm, while type 5 NFC tags use ISO 15963 and have a range of 1 m. NFC has three operating modes specified in the standard: Read/Write, Peer-to-Peer, and Card Emulation. Read/Write mode is the typical mode used in NFC where you have a dedicated tag and reader; the tag is a passive tag, while the reader can be mains or battery powered. Peer-to-Peer is performed between two NFC devices, which switch between reader and tag modes. This NFC method is either mains-to-battery or battery-to-battery. Card Emulation is the simplest mode, where an NFC device emulates a smart card. The NFC device is normally battery powered.

Three significant forces are pushing towards a future where batteryless Near Field Communication (NFC) applications become a standard. These forces include improvements in ultra-low-power microcontrollers, the rise of affordable NFC energy harvesting integrated circuits (ICs), and the widespread integration of NFC readers in most smartphones. These dynamics fit together to create a standard of wireless communication that does not rely on conventional power sources, opening up possibilities across various industries, daily life, and new applications.

The reason for the focus on batteryless NFC is the combination of data and energy transfer in a single communication protocol. This differs from the hybrid approach, which uses a combination of two differing protocols. An example of a hybrid system can be seen by combining [62] solar cells with Bluetooth BLE or Wi-Fi energy harvesting and infra-red. Batteryless NFC uses one protocol, which means simplicity over the hybrid approach. As batteryless NFC does not include a type of significant energy storage, such as a battery or supercapacitor, this leads to the system being powered by an external source in the batteryless NFC tag. This is achieved through an NFC reader through near-field coupling.

Another term associated with the batteryless NFC concept is passive–active NFC. Passive–active NFC is a subset of passive NFC communication, where an NFC tag can be powered externally from an NFC reader and does work. The work that is performed can be data transfer or sensor reading. The difference between passive and passive–active is that tasks outside the NFC protocol can be achieved [63], which means external memory checking where the data are transferred or confirmed by a microcontroller or temperature sensing where sensor data are sent over NFC. Batteryless NFC can be included in the passive–active NFC concept; however, the difference between passive and passive–active NFC is that passive–active NFC can have a battery or be connected to the mains but can also switch states while including the batteryless mode. This gives flexibility, as the system is not confined to one mode of NFC but can switch between modes.

A batteryless NFC tag contains three main parts: the transmission system, which contains the antenna and matching circuit; the NFC protocol, which is contained on a dynamic NFC IC; and the work part, which contains sensors and a microcontroller IC. The transmission system is a loop antenna matched to 13.56 Mhz with a corresponding matching circuit if necessary. The size of the antenna can vary significantly depending on the use case, size and range of the device. With the majority of NFC antennas being loop antennas [64], a typical NFC antenna size is 30 mm $\times$ 40 mm; however, the overall size can be reduced significantly [65]. One type of NFC antenna is the PCB loop antenna. This type of antenna can be as small as 2.4 by 2.4 mm by having a dual-layer PCB loop antenna; however, this will affect the range of energy that is achievable. In designing this type of antenna, a design choice is energy harvesting range vs. antenna size.

There are a range of dynamic NFC tags used for batteryless NFC such as the M24LR, ST25DV16K, NT3H211, and RF430FRL152H. This range of ICs has been achieved by the development of batteryless NFC and passive–active NFC; these ICs are a range of NFC type NT3H211, which is a type 2 NFC tag using ISO 14443, while M24LR and ST25DV16K are type 5 NFC tags using ISO 15963. The most unique is the RF430FRL152H, which also uses ISO 15693. However, it is a combination of a dynamic NFC IC tag and a microcontroller in a single IC, whose stated use is as a sensor transponder [66]. These ICs have opened the door to easy access to batteryless NFC; there has been a switch from chipless batteryless design in the 2010s to use commercial dynamic NFC ICs in the 2020s.

However, as mentioned in the discussion of RFID, the factor range of an NFC tag system varies significantly depending on a range of factors. The range of a system is critical in batteryless NFC, as this determines the working distance using smartphones. The range of batteryless NFC is limited to 8–45 mm, with the typical batteryless NFC application having a range of 20 mm. ISO 14443 is limited to a range of around 10 cm; however, type 5 NFC tags, which are designed for industrial applications, can have a stated range of 100 cm. However, this means an industrial NFC reader can be used to power the system to increase the range of the system. A system is shown with increased range using an industrial NFC reader and increased power transfer by using wireless power transfer and a wireless power transfer antenna [67].

As seen in Table 4, there is a range of researched applications for batteryless NFC with a varied combination of both NFC ICs and microcontrollers. The applications range from industrial, agricultural and medical use cases for batteryless NFC. The range of the batteryless applications displayed in Table 4 only uses smartphone NFC readers for range measurements compared to industrial NFC readers, and as such, the range is below 45 mm for all applications. The NFC Bicycle Tyre Pressure Sensor [68] only has a range of 8 mm. This is due to the small antenna size of 14 × 48 mm; however, with an alternative reader, this range could be extended.

Table 4. Table comparing NFC applications.

Application Name	Year	Range	NFC IC	Microcontroller
Batteryless soil moisture measurement system [69]	2018	20 mm	M24LR	ATTINY85
Batteryless NFC Sensor for pH Monitoring [70]	2019	18 mm	M24LR	ATTINY85
Batteryless NFC Bicycle Tire Pressure Sensor [68]	2021	8 mm	NT3H211	ATTINY85
Smart Bandage With Wireless Strain and Temperature Sensors [71]	2020	43 mm	RF430FRL152H	RF430FRL152H
Smartphone-Based NFC Potentiostat for Wireless Electrochemical Sensing [72]	2021	20 mm	SIC4341	N/A
Concertina-Shaped Vibration Energy Harvester-Assisted NFC Sensor [73]	2022	45 mm	ST25DV16K	STM32L031
glucose monitoring via smartphone [74]	2023	N/A	SIC4341	N/A
Total Minerals in Drinking Water via Smartphone [66]	2021	30 mm	M24LR16E	MSP430FR2433
Dosimeter tag for ionizing radiation [75]	2023	N/A	M24LR64E	PIC16LF1703

The range of batteryless NFC applications shows how batteryless NFC is versatile and can be used to solve many tasks. The reason for this is that NFC is a widespread protocol with use cases in payment systems, which has led to the integration of NFC readers in smartphones while also being a wireless protocol used for identification, which competes with QR codes. One of the main applications of batteryless NFC is in the medical field, where its use could be widespread to include sense internal or external sensor measurements. Another example system shows a smartbandage that uses an

RF430FRL152H [71]. It uses a combination of strain and temperature sensors to collect data; however, it performs no data analysis internally and stores the data in ROM for transmission over ISO 15963. This system is a typical sensor system, which is the most common use case for batteryless NFC sensor-based systems, which typically uses a microcontroller to input and convert sensor readings into a dynamic IC memory storage in the case of the RF430FRL152H. This is performed inside a single IC compared to other examples which have a dedicated NFC IC. Another researched use case is glucose monitoring [74]. This was performed using a SIC4341 device, which is a dynamic NFC IC; this system received data from the glucose sensor and transmitted them through NFC. Both systems described above use a smartphone as the NFC reader and display the data in a smartphone app. The advantage of this is that any user with a smartphone with NFC capabilities can use this system.

Batteryless NFC sensors are the primary focus of batteryless NFC research. In [69], an example is given of a soil moisture measurement system that uses an M24LR NFC IC while using an ATTINY85 as the MCU. This system, during work, uses approximately 1 mA of power, which is performed using a SIC4341, a dynamic NFC IC. This system receives data from the glucose sensor and transmits the data through NFC. The supply voltage varies from 2.7 to 3.3 volts, and the system includes three sensors which measure humidity, temperature, and soil water content. This system shows a typical application and the responding power levels [76]. The maximum claimed NFC power is 10 mA at 3.3 V. This comes from the SIC43XX series; however, it uses ISO14443, so the range is limited. M24LR-E-R has a claimed maximum 6 mA at 3 V. The soil moisture measurement system has a range of 20 mm. This is mostly due to its antenna size and antenna design and is limited by the reader's choice of smartphone. This range would increase if an industrial reader were used, which is viable with ISO 15963,

One of the main developments that could use batteryless NFC is smart factories or smart devices to perform batteryless over-the-air (OTA) programming or transmission. This can be performed in a batteryless way in passive–active systems either in the field or in a controlled environment such as a factory. This could be a batteryless wireless in-application programming into an embedded system, possibly without the need to power the system or to a system with no other communication protocol. This could be used to embed sensors without the need for energy storage and be able to communicate [77]. OTA programming also has a range of benefits, as programming can be performed quickly and wirelessly, so there is no need to remove packaging while also having a way to internally read the device data as an advanced label. Where this becomes specific for batteryless NFC is the advantage of confirming that the communication was successful, as well as being able to add security features and conduct testing.

5. Power Consumption of Short-Range Wireless Communication Applications

Short-range wireless communication covers various standards and protocols with varying power consumption based on application. RFID and UWB, which focus on identification and location, respectively, are low-power protocols with low amounts of static data transfer. This is comparable to BLE and batteryless NFC, which involve more dynamic data transfer, while Wi-Fi is focused on data transfer compared to power consumption. The type of system, whether it is batteryless, battery powered, or mains powered, plays a significant role in determining the power requirements. This factor is crucial in selecting the most suitable wireless communication protocol, as each system type has different power consumption needs.

Dedicated ICs vs. system on a chip differ between protocols; BLE has a range of different chipsets. The power consumption of different chipsets varies massively with operation and hardware power consumption; however, an estimation of processing power vs. communication power can be achieved with the Intel A-101 having an average current of 0.089 mA and a 21.338% processing vs. communication ratio, Cypress CY8CKIT-042-BLE having an average current of 0.018 mA and a 23.02% ratio, and the NXP FRDM-

KW41Z having an average current of 0.036 mA and a 28.07 ratio [41]. SOCs with a single microcontroller are naturally more efficient than dedicated ICs due to the need for two simultaneous processors to be active. This can be seen in the batteryless NFC operation in [69]. The M24LR dynamic NFC IC power consumption is 0.4 mA. The ATtiny85 power consumption is 0.3 mA, and the ratio is 47% when the timer is taken into account.

While communication transmission power consumption takes up a significant proportion of the overall power consumption during active operation, there is a limit to reducing the power consumption unless we want to reduce the range or communication duty cycle of the system. Microprocessors are the main power drain during the non-active operation of the system, and reducing the power consumption of the microprocessor either during active or non-active operation can make a batteryless system viable or increase the battery life of battery power systems.

Comparing the power consumption of different short-range wireless communication applications is challenging due to the varying factors between systems and applications, such as duty cycle, the range required, the microprocessor used, and the varying number of sensors used in data-gathering devices. To avoid this problem, the minimum system requirements must be the focus. These limits determine the feasibility and limits of short-range wireless communication, which must be considered.

The transmit power consumption is based on different protocols, Bluetooth 102.6 mW, Wi-fi 722.7 mW, Zigbee 73.5, UWB 749.1 mW [78], and RFID reader 180 mW [79]. However these values only show the peak power required. These power requirements set a limit on pure batteryless-based solutions, as energy storage is required for high-power short duty cycle transmission compared to a battery-based system, where the average power consumption is the important distinction.

Ultra-low-power microcontrollers are a critical part of dynamic short-range wireless communication systems, as they limit the power consumptionin dynamic applications such as BLE, Zigbee, and batteryless NFC.

6. Review of Ultra-Low-Power Microcontrollers

Historically, ultra-low-power microcontrollers were distinguished from standard microcontrollers by their unique characteristics. In 2000, ultra-low-power microcontrollers [80] had unique features compared to standard microcontrollers. One of the main differences was the supply voltage, with some ultra-low-power microcontrollers having a supply voltage of 1.8 V, whereas standard microcontrollers had a supply of 3.3 V. The other factor was the inclusion of multiple low-power modes compared to the standard, which included just a sleep mode. In 2024, ultra-low-power microcontrollers are more difficult to distinguish from their standard series counterparts. This is evident in the STM32 series of microcontrollers, where the STM32L0 series has a supply voltage range of 1.65–3.6 volts, and the STM32H723 high-performance microcontroller has a supply voltage range of 1.62–3.6 volts, in addition to a number of low-power modes and a 32 kHz internal clock. Regular microcontrollers incorporate ultra-low-power microcontroller features. However, the primary distinction between standard and ultra-low-power microcontrollers lies in their respective purposes. An ultra-low-power microcontroller aims to control and reduce power consumption. This is typically accomplished in two distinct ways. In work/run mode, the objective is to complete as much work as possible while consuming the least amount of energy possible. In sleep mode, the sole objective is to consume as little energy as possible.

Many factors affect ULP microcontrollers, but the most critical is power consumption. The goal of ULP microcontrollers is to have the lowest possible power consumption while getting the most work done, compared to regular microcontrollers, where getting work done fast and efficiently is the most important factor. Power consumption is affected by both hardware and software factors; the main hardware factors are supply voltage, transistor size, and the number of cores. The software factors include low power modes, efficiency of work, and length of work.

The divergence between regular and ULP microcontrollers occurred in the early 2000s. ULP microcontrollers have the goal of the lowest power consumption, which enhances battery life, as the battery capacity is not growing as fast as other associated technologies. Decreasing power consumption is one way to increase lifespan without affecting the size of the battery; this is crucial in areas such as spacecraft, medical implants, and IoT devices. ULP microcontrollers have also led the way in energy harvesting and, in the future, batteryless technology. Another divergence occurred in 2000. The transistor size in both CISC and RISC products were significantly closer than in the modern era, with the size of the transistor being 250 nm for a workstation, 350 nm for an embedded system, and 500 nm in the year 2000, while today, typically a CISC core is 7 nm [81], while the RISC typical core size is 65 nm [82].

The supply voltage of both the internal transistors and the minimum supply voltage of a microcontroller are vital for ULP microcontrollers and have a significant impact on low-power performance. The reduction in the supply voltage of transistors dropped by around 40% from 2003 to 2020 as shown in Figure 3. The drop from 1.2 V to 0.7 V means it is possible to reduce the power consumption of ULP microcontrollers; the issue is that the standard for ULP microcontrollers is still 1.8 V and has not shifted since the mid-2000s. Some series of microcontrollers have reduced the supply voltage such as the STM32L, which has a minimum supply voltage of 1.65 V; however, the reduction is minimal, and no mainstream chipset has reduced their supply voltage significantly. The problem is that the supply voltage is only reduced when a new series comes out, and this is normally less than two times the transistor voltage. This can be seen in STM32, which released in 2014. The 2013 supply voltage was $0.86 \times 2 = 1.72$. A mainstream series of 1.4 V might be possible by 2025. The supply voltage will stall due to expected technological barriers. This will cause major issues, as reducing the supply voltage is one of the two ways to reduce power consumption without affecting performance.

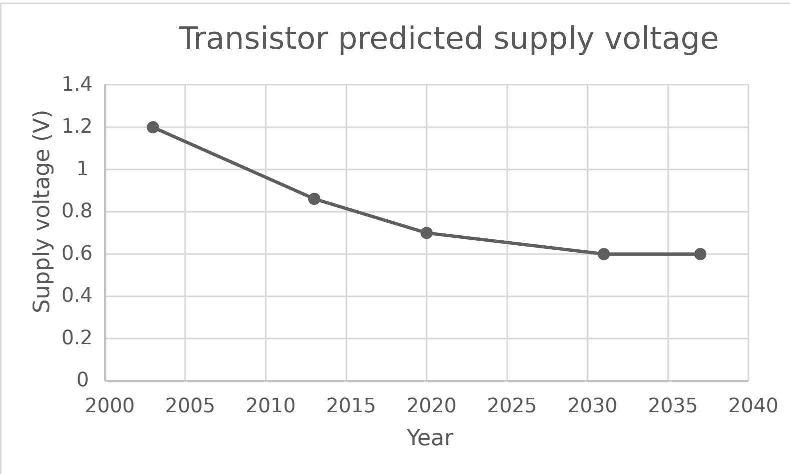

Figure 3. Figure microcontroller predicted supply voltage [81] .

The selection of the microcontroller for low-power short-range communication is crucial; with different protocols having differing requirements, the challenge is selecting a microcontroller for an application, with Table 4 showing that there is a range of microcontroller options for a single application. What is known is that the slowing of power consumption optimization [83] is making generational change smaller and causing the older microcontrollers to still have relevance.

7. Future Discussion

The current state of short-range communication protocols is heavily influenced by the prevalence of battery-powered devices. The shift happened around 2005 when protocols were specifically modified, such as in the case of BLE, or created, such as NFC. The change occurred due to a combination of factors, including the [84] development and improvement of battery technology, as well as the development of ultra-low-power microcontrollers, hardware improvements, and the addition of software and power consumption optimization. The shift to low-power embedded systems and battery power devices has led to a range of use cases, which has led to the development of BLE, NFC, and low-power Wi-Fi. One of the questions concerning the development of wireless communication protocols is: does the protocol develop first, or does the use case? One real-world example of the modification of an existing protocol is Bluetooth, as the protocol was already developed but was modified to fit low-powered devices, while NFC was built specifically for the use of contactless payments [85]. However, there is continued research into future use cases of current protocols such as Bluetooth localization and passive RFID sensors such as WISP.

What is happening to batteryless technology is that existing protocols such as NFC are being used without modification while standalone platforms such as NFC-WISP [86] are in development. Batteryless technology is used in RFID and NFC; however, without modification, they do not perform any work and are static devices. However, passive–active NFC changes this, making a use case where either a sensor or over-the-air programming is viable without an additional component added to the system. This is comparable to a hybrid communication-energy-having system, which, while having advantages, is less desirable than a single protocol to perform both energy and data transfer.

There are many challenges ahead to continue the evolution of ultra-low-power systems; for example, microcontroller development is coming to a physical limit Figure 4 in the size of transistors and supply voltage. The current trend of improvements to hardware power consumption optimization might lead to the development of more software-based power consumption techniques. The development of batteryless and hybrid systems that rely on external power sources are currently being researched as seeming viable to be included in embedded systems [54]. Wi-Fi energy harvesting is an example where direct inclusion into low-power applications that are currently in use, such as TV remotes, clocks, and smoke alarms, will lead to the inclusion of hybrid technology. The adoption of batteryless systems using RFID and NFC technology would lead to the optimization and maybe integration of batteryless NFC systems into one platform. This could lead to internal sensors, and the application for internal battery sensors includes areas from construction to medical use. The use of tiny internal batteryless sensors could lead to an increase in health monitoring [87], and implants could help with patient monitoring. Another use is in long-life sensors such as inside concrete [67] or insulation, which would be used to monitor temperature.

Figure 4. Figure of microcontroller predicted transistor size [81].

8. Conclusions

The main conclusion from comparing different short-range wireless communications is that protocols can evolve to conform to different application scenarios, for example, the change from Bluetooth to BLE or NFC to batteryless NFC. Additionally, protocol optimizations such as those seen in Wi-Fi are critical to keeping protocols prevalent. Research is continuing to advance the current protocols to improve operational parameters such as power consumption, range, data rates or to add new, more advanced, features.

Factors influencing IoT and embedded systems contribute to the growing interest in short-range wireless communication. The analysis in this paper encompasses the customary short-range communication protocols and technologies currently used. The current era is focused on battery-powered, low-power communication, and this will be the focus for the majority for many years; however, physical limitations in ultra-low-power microcontrollers and battery technology will seem to lead to an end to hardware power consumption growth. This can be seen by the slowing of microcontroller size and supply voltage reductions [88]. This has led to the development of multi-core microprocessors, and the industry believes in the innovation of core stacking. This, however, conflicts with the ultra-low-power microcontroller goal of low power consumption, as this does not help with lowering power consumption, as transistor size and supply voltage are crucial for lowering power consumption. For a microcontroller, this will lead to a stagnation in hardware power consumption.

Another increasing factor in modern-day IoT and embedded systems is the increasing number of devices, as well as the goal of being able to make smart devices with smaller size and longer life. This has led to an increase in IoT device research; however, some tasks are impractical with current research and technology. The aim is to overcome physical hardware hurdles for smaller devices with energy-harvesting solutions and software solutions.

Short-range wireless communication has many solutions, depending on the application and use case. It connects at least two systems together in a range of different ways; with the protocols in this review, only the most widespread protocols were discussed, but as seen, Bluetooth, Wi-Fi, and optical communication are still being developed and modified with adjustments, and new versions are still in development. While RFID has not had any major changes or updates, it is still being updated, with ISO 15963 having a specification in 2020. There is also new long-range communication, such as ZigBee or Sigfox, which can be used to connect short-range devices to low-power networks. What can be seen is the evident evolution in short-range wireless communication, even though existing protocols seem to have become dominant in some application scenarios.

Batteryless and hybrid energy systems are rapidly evolving and have numerous advantages over traditional systems as highlighted in this review. Although not yet mainstream, the applications and use cases for this technology are immense. One of the most significant advantages of hybrid systems is their lifespan, which can last for a few years in the right conditions. In contrast, a batteryless system could theoretically last for an indefinite period. To incorporate these systems into an IoT or smart system, a low-power communication protocol that can be combined with energy harvesting is essential.

Author Contributions: Conceptualization, literature review, analysis, conclusions and original draft, B.B.; writing, reviewing, editing and supervision, J.W., M.J.R. and M.A. All authors have read and agreed to the published version of the manuscript.

Funding: Knowledge Transfer Partnerships UK (KTP 13449): Innovate UK and Emergency Lighting Products Ltd.

Data Availability Statement: Data is contained within the article or cited items.

Acknowledgments: CSEE Department at University of Essex.

Conflicts of Interest: As author Martin Afford was employed by the company Emergency Lighting Products Ltd. All authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data or in the decision to publish the results.

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