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A Survey on Evolved LoRa-Based Communication Technologies for Emerging Internet of Things Applications

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Abstract: The concept of Internet of Things (IoT) greatly extends the coverage area that human being is able to perceive, access, and even control. By connecting various "Things" to the Internet, the IoT makes it possible to measure and manage the physical world as needed. As one of the most widely adopted Low Power Wide Area network technologies, the Long-Range-Radio (LoRa) has the features of long range, low power, and robustness, and thus plays an important role in building IoT applications where IoT objects are connected to the internet at affordable costs. Since the development of LoRa, many IoT applications have adopted LoRa and achieved success in the market. Currently, IoT technologies keep evolving towards different fields, giving rise to multifarious IoT applications including industrial IoT, smart city IoT, healthcare IoT, and direct-to-satellite IoT. In the meantime, LoRa also keeps developing and finding its position in various IoT applications either as a main or complementary player. The objective of this survey is to (1) provide a fundamental understanding of the LoRa technology; (2) explore research activities studying LoRa based communication systems for new IoT applications; and (3) demonstrate how the LoRa technology works together with other technologies to deliver better IoT services to end users.

Keywords: internet of things; long range radio; low power wide area network

1. Introduction

The Internet of Things (IoT) refers to a set of technologies cooperating to network the physical world [1], and aims to interconnect everything and enable proper processing on the collected data in order to support high-level decision making. Early in 1999, Kevin Aston [2] used the term "Internet of Things" to describe a system using radio frequency identification (RFID) to keep tracking and monitoring on goods in supply chain management. In his idea, an object is possible to be automatically recognized, recorded and analyzed if it can be identified by machines. As defined by ITU (International Telecommunication Union) [3], an IoT system consists of three components: the device, IoT and thing. The device is "a piece of equipment with mandatory capabilities of communication and optional capabilities of sensing, actuation, data capture, data storage and data processing". The IoT refers to "a global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies". The thing refers to "an object of the physical world (physical things) or the information world (virtual things), which is capable of being identified and integrated into communication networks". A simplified IoT application is shown in Figure 1.

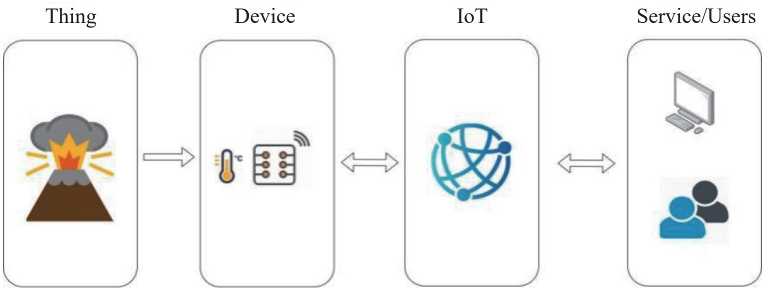

Figure 1. Example of an IoT application.

A volcano (i.e. the Thing) cannot talk to human being until its characteristics is "translated" into a digital format by "Device", e.g. a temperature sensor. Since it is not convenient to have personnel watch the sensor all day long, it is necessary to have a way to transfer data to a remote site. Deploying a temperature sensor (i.e. devices with optional capabilities) with a communication module (i.e. device with mandatory capabilities) which has connections to the Internet is considered as a proper solution, namely IoT. The challenges of building an IoT system come from the establishment of links between the network and the far-away physical devices, e.g. a refrigerator, an air conditioner and a temperature/humidity sensor. Such devices usually work individually, generate a small volume of data, and sometimes ask for low power consumption. For example, an electricity meter is installed in a metal cabinet in the cellar of a house, and is able to report energy readings every 15 minutes. Each reporting consists of a four-byte meter reading and a 13 bytes overhead [4]. Typically, a community has hundreds of meters in operation. Since meters are installed in the cellar of house, deploying cables for meters to be connected to network may have difficulty and therefore, applying wireless communication seems to be a promising solution [4−6]. However, wireless communication is prone to failures due to various factors, including building materials, interior structures of houses/buildings and other radio systems coexisting in the same area [7]. To obtain better link budget, the narrow band (NB) wireless technology is a preferable choice that outperforms the wide-band wireless technology in the processing gains and radio sensitivity, and is usually summarized as the low power wide area network (LPWAN) technology [8].

As concluded in [9], typical LPWAN technologies include long range radio wide area network (LoRaWAN), NB-IoT, SigFox, and Wi-Sun that are designed for connecting large number of low-cost, low power consumption and low throughput end devices with large coverage areas. Generally, LoRaWAN and SigFox can achieve a convergence area larger than 10 kilometers' communication range [10]. NB-IoT makes use of the widely deployed base stations to achieve city level coverage. Wi-Sun is an enterprise–grade mesh network technology [11]. Each of the aforementioned technologies has its own characteristic for certain scenarios. For instance, LoRaWAN is suitable for applications requiring low data rate, low power consumption, and feasible deployment regarding private or public network access. SigFox is appropriate for applications asking for ultra-low data rate and power consumption. NB-IoT is a low power consumption technology but requires public network access. Wi-Sun is good for smart city applications but needs complex network operation management.

This survey aims to (1) introduce the concept of LoRa techniques and provide a fundamental understanding of LoRa communication; (2) explore research activities studying LoRa based IoT applications; and (3) demonstrate how LoRa techniques working together with other technologies to deliver better services to end users in emerging IoT application areas. Particularly, the research activities carried out to resolve LoRa communication issues for specific IoT areas are studied, such as communication protocol, performance optimization, and application deployment. There are lots of LoRa related survey papers made by researchers that summarize and discuss LoRa technologies. In [12] authors made comparisons between LoRa and NB-IoT at issues of physical layer design, battery consumption, network coverage, deployment model and cost. In [13,14], the authors provided a comprehensive survey for LoRa technique, including performance of modulation technology, Medium Access Control protocol design, LoRa security and list of LoRa applications. Moreover, in [15], the LoRa technique was analyzed from down to top to show current research effort on improving performance metrics related to LoRa. Compared with previous surveys, our contribution is to summarize the use of LoRa along with requirements in different IoT application fields. Continuously emerging IoT applications/fields are the major motivation in driving the evolvement of LoRa techniques, giving rise to not only new enhancement and optimization at certain technical points, but also new paradigm of LoRa application along with other technologies. As such, it is of great importance to review the LoRa research by taking it as an important constituent part of the IoT applications.

The rest of this survey is organized as follows: Section 2 discusses characteristics of different IoT fields and their requirements to LoRa technique. Section 3 introduces basic concept of LoRa radio communication and research studies on LoRa modulation schemes and performance optimization. In Sections 4, 5, 6 and 7, the adoption of LoRa technique in different IoT areas, including industrial IoT, smart city IoT, direct-to-space IoT and healthcare IoT, is reviewed and discussed. Conclusion about the development trend of LoRa in the concept of IoT is made in Section 8.

2. Iot and LoRa

Exactly speaking, the IoT is not an individual technology but a comprehensive concept covering tremendous technologies and evolving with the development of information and communication technologies. The IoT is in fact an evolution of mobile, embedded applications and everything that is connected to the internet [16], which generates urgent needs for a new paradigm of data collection and processing. Furthermore, the IoT is an expansion of conventional network technologies in a sense whose core concept is to build interconnections among "Things" and further have the physical world networked.

Nowadays, more and more IoT related applications emerge as either new market spaces develop or existing technologies upgrade, which pushes an evolution of IoT technologies in different fields. One feature of IoT applications is the diversity of communication requirements which is also the main difference between conventional communications and IoT communications. In conventional applications, the Internet connected devices, such as computers, tablets, and mobile phones, are mainly controlled by humans with stable network connections, whereas in IoT applications, the scope of devices connecting to the Internet are extended to every kind of devices, including sensors, actuators and tags [17]. Development of the IoT contains not only conventional systems, but also comprehensive interactions introduced by "Smart Objects" (e.g. sophisticated smart gadgets, smartphones, and smart vehicles) which exhibit different degrees of intelligence in data processing and communication with conventional systems [18].

To be specific, the Video-on-Demand service is a typical application using conventional communication technologies. Video programs are pre-stored on servers, and TV terminals can request certain program from a server nearby. The communication content is almost fixed and the traffic over communication links is predictable. Note that the entire system works in a closed-loop manner as insertion of new programs, increment of subscriptions, and capacity of networks are always under control. Using distributed sensors to help manage smart agriculture is a popular application of IoT. Various sensors connect to local edge servers to provide real-time sensory data critical to the crops. The edge server makes decisions, e.g. irrigation or sowing, based on the received data. The source of data comes from real-world, which means the major challenges imposed on IoT communications come from aspects of data volume, variety, veracity and velocity [19].

Many IoT applications require long range, low data rate, low energy consumption and cost effective wireless communication [20]. As one of LPWAN technologies, the LoRa has the most technical advantages required by IoT applications. Particularly, the open design (except for physical layers) feature of the LoRa provides great convenience for researchers and developers to study and use. In general, IoT applications requiring the involvement of LoRa technique possess two common characteristics: wireless communication in difficult radio environment and low data rate [21−23]. Difficult environment refers to interferences and long range communications that many IoT applications have to face when deploying networks. Low data rate means only IoT applications requiring small data can adopt LoRa. In the following sections, the LoRa radio and representative IoT fields in which LoRa is a main or supplementary player in building wireless communication links are selected and discussed to explore research activities made for the use of LoRa. The typical IoT fields include industrial IoT, smart city IoT, healthcare IoT, agriculture IoT, and DtS-IoT [17,24].

3. LoRa Radio Communication

LoRa is a narrowband communication technology patented by Semtech [25], and is a kind of physical layer modulation technologies that utilize Chirp (Compressed High Intensity Radar Pulse) Spread Spectrum (CSS) to achieve significant long communication range and robustness to interference on the premise of low power consumption [26, 27], and this is also the key to make LoRa stay competitive compared with other LPWAN technologies. A comparison between LoRa and other mainstream IoT wireless communication technologies is listed in [28−31].

The IoT wireless communication technologies listed in Table 1 can help end devices build links to networks. However, such technologies can only be applicable to certain application fields due to their technology differences. NB-IoT and SigFox can achieve long range communication, and are unsuitable for applications requiring use of local area networks. This is because NB-IoT and SigFox establish direct links between end devices and operators' networks (i.e. public networks). Wi-Fi and Bluetooth can provide relative high data rate and are suitable for multimedia applications. As a trade-off, Wi-Fi and Bluetooth consume more energy compared with other technologies. ZigBee is a low cost and low power consumption technology for short-range IoT applications, and thus has limited coverage. In contrast, LoRa can provide dynamic radio coverage for large-scale IoT applications which require long lifetime, whereas the main shortage of LoRa comes from its low data rate.

Table 1 Comparison of wireless IoT communication technologies

	LoRa	**SigFox**	**ZigBee**	**Bluetooth**	**Wi-Fi**	**NB-IoT**
Technology	Proprietary PHY, Open MAC	Proprietary	IEEE802.15.4	IEEE802.15.1	IEEE802.11	3GPP
Spectrum	Unlicensed band					Licensed band
Frequency	Sub-GHz, 2.4 GHz	862−928 MHz	2.4 GHz	2.4 GHz	2.4 GHz	700−2100 MHz
Modulation	CSS	D-BPSK,GFSK	DSS	FHSS	QPSK,BPSK,QAM	BPSK QPSK
Rate	0.018−37.5 kbps[1] 31.72−253.91 kbps[2]	100 or 600 bps	250 kbps	~2 Mbps	11 Mbps 54 Mbps or more	~250 kbps
Bandwidth	7.8−500 kHz, 200−1600 kHz	100 Hz, 600 Hz	2 MHz	1 MHz	20 MHz, 40 MHz	180 kHz
Coverage	1−10 km	10−40 km	~100 m	~10 m	~100 m	15 km
Deployment	Start, mesh	Operator	Mesh	Master-slave, Mesh	Star, Ad-hoc	Operator
Security	AES128	AES128	AES128	Secure Simple Pairing, AES-CCM	TKIP, AES	LTE security
Rx sensitivity[3]	−148 dBm	−133 dBm	−102 dBm	−82 dBm	−90 dBm	−114 dBm
Battery life	+10 years	+10 years	100−7000 days	1−7 days	0.1−5 days	+10 years

[1] LoRa at Sub-1 GHz

[2] LoRa at 2.4 GHz

[3] Depend on configuration

Application scenarios in which LoRa outperforms than other technologies include logistics tracking, assert tracking, smart agriculture, healthcare, etc. [32]. An important characteristic of these scenarios is uncertain communication range, which can be a few meters or up to a few kilometers. Excellent design of receiving sensitivity makes LoRa capable of covering large area with limited power supply. On the contrary, it is clear that LoRa is not suitable for high data rate applications whose major candidates are Wi-Fi or Bluetooth based technologies. Performance of LoRa modem is configurable through a few parameters, which typically include: spreading factor (SF), bandwidth (BW), and coding rate (CR) [33].

- Spreading Factor (SF)

SF represents the level that the spread spectrum algorithm works on each bit. The higher the SF is, the more spreading code will be used for each bit. Consequently, the receiving sensitivity at the receiver side improves c. LoRa supports SF ranges from 6 to 12.

- Bandwidth (BW)

Bandwidth is directly related to the data rate. If a higher bandwidth is used, a higher data rate can be achieved at the cost of reduced receiving sensitivity. In the contrary, a smaller bandwidth is helpful in obtaining better receiver sensitivity, but data rate decreases accordingly. The BW option supported by LoRa ranges from 7.8 kHz to 500 kHz (at Sub-1 GHz frequency band).

- Error Correction Rate (ECR)

Cyclic error coding is employed as the forward error detection and correction scheme in the LoRa technology. The higher the CR value is, the stronger capability of error correction can be achieved. However, additional overhead is included in transmission which reduces effective user data rate. LoRa modem supports CR from 4/5 to 4/8. The overhead ratio for different CR is shown in Table 2

Table 2 Cyclic coding overhead

Coding Rate	**Overhead Ratio**	**Cyclic Coding Rate**
1	1.25	4/5
2	1.5	4/6
3	1.75	4/7
4	2	4/8

LoRa device supports various data rate from 0.018 kbps to 37.5 kbps. Corresponding receiving sensitivity ranges from −111 dBm to −148 dBm, and is achieved by selecting different combinations of SF, CR and BW. Table 3 listed below shows typical parameter settings and data rate achieved at 868 MHz.

Table 3 LoRa modem performance

BW (kHz)	SF	CR	Data Rate (bps)	Receiving Sensitivity (dBm)
125	6	4/5	9380	−118
	12	4/5	293	−136
62.5	6	4/5	4688	−121
	12	4/5	146	−139
20.8	6	4/5	1562	−128
	12	4/5	49	−144
10.4	6	4/5	782	−131
	12	4/5	24	−147

As stated in [34], LoRa can provide over 150 dB link budget for long range communication. When installed at fixed position and configured with certain settings (14 dBm tx power, BW = 125 kHz, SF = 12), a LoRa gateway can achieve 62% packet delivery rate at range of 15-30 km, 88% and 85% at range of 2 and 5 km. Regarding mobile situation, a reliable communication link can be established if relative speed is lower than 25 km/h. Significant packet loss is observed when relative speed is close to or over 40 km/h. The test results show that LoRa modem is capable of providing service in either stationary or mobile scenarios.

IoT applications, such as environment monitoring, smart metering, plant monitoring, etc., require massive and large deployment, but very few data payload which could be as small as one byte to indicate On or Off states. The corresponding data report interval could be as slow as 1 packet/day or 1 packet/hour. The key point here is long range communication and low power consumption. LoRa achieves this objective with the use of CSS. Since LoRa is a proprietary technique, researchers mainly focus on performance study. Relevant proposals of physical layer optimizations are based on general principles of CSS. The important features of LoRa communication which receive wide interests from industry sections are long range communication capability, robustness to interferences, and low power consumption. Mroue et al. made an analytical study along with simulation work to explain and improve LoRa-based BER (Bit Error Rate) expressions [35]. The proposed BER expression is more accurate compared with the conventional error probability of CSS by introducing a few parameters such as symbol frequency, sampling frequency, signal-to-noise and implementation loss. In [36], mathematic expressions describing generation and demodulation of LoRa signal were made. In addition, authors in [36] proposed a simplified filter design to reduce number of coefficients of digital filters in the baseband process at the receiver. Simulation results showed that the design can achieve satisfactory performance of symbol error rate at a cost of slightly increment of SNR (Signal-to-Noise Ratio) loss.

As the LoRa technology may be used to collect sensory data in a dense network, its feature of the "orthogonal spreading factor" is usually taken to provide simultaneous transmission capability, i.e. multiple communications are allowed to happen simultaneously as long as they employ different spreading factors. However, such transmission might be inaccurate since the achievement of "orthogonality" needs certain condition, i.e. the threshold of SIR (Signal-to-Interference Ratio). In [37], authors implemented simulation and practical experiments to determine if desired LoRa communication can be successfully completed at the presence of "interfering LoRa signal" with different spreading factors. The result showed that by average, a 16 dB co-channel rejection value should be satisfied to have desired communication successfully completed. It is for the reason that the receiver takes the interfering LoRa signal as a chirped waveform (a wide-band spectrum) and tries to look for a peak value to synchronize with the desired signal whose strength should be 16 dB higher than the interfering signal. This finding indicates that applying different spreading factors may not be sufficient to build independent communication channels if interfering LoRa devices are close to the receiver during communication.

In fact, LoRa is one de-factor standard of IoT technologies for long range communication where there might be hundreds of meters or kilometers between a LoRa end device and a LoRa gateway. As a kind of NB wireless technologies, LoRa can achieve longer communication range than that of wideband wireless communication technologies, e.g. WiFi, and Bluetooth, with given transmission power (usually it is a mandatory requirement made by local authority for radio usage at industrial scientific medical (ISM) band in different regions). However, there is a trade-off between communication range and data rate. NB systems can support low data rate since a small bandwidth has limitations in channel capacity according to Shannon-Hartley theorem [38]. Obviously, low data rate means a long radio propagation time which results in high possibility of wireless conflicts between different radio communications. For example, LoRa devices support receiving sensitivity low to −136 dBm when the spreading factor is 12, bandwidth is 125 kHz and nominal data rate is 293 bps. A short message whose length is tens of bytes may last for a few seconds over the air, and this significantly increases the possibility of radio conflicts and interferences.

A dilemma of IoT applications is the use of NB radio systems to implement large scale and dense deployment, e.g. utility meter reading, smart agriculture, and environment monitoring. Many research carried out at the physical layer of LoRa-like modulation schemes focus on data rate improvement on the premise of keeping receiving sensitivity at an acceptable level. Authors in [39] proposed a novel design of chirp transmitters and orthogonal hirp generators (OCGs) to support a wide range of spreading factors and bandwidth at a low cost. In addition, a phase-shifted CSS (PS-CSS) was proposed to increase transmission rate by which a maximum of 33% improvement (spreading factor is 6) was made compared to conventional CSS technologies.

In order to improve spectral efficiency and energy efficiency, alternative chirp spread spectrum techniques, in-phase and quadrature CSS (IQCSS) and discrete chirp rate keying CSS (DCRK-CSS), were proposed in [40]. As claimed by the authors, IQCSS can double throughputs compared with LoRa. DCRK-CSS can increase the throughput up to 50% under certain conditions. The throughput optimization brought by the two schemes is obtained using the same transmission power when compared with LoRa modulation, and this means less energy will be consumed as shorter time is required to complete transmission. An idea of using index modulation (IM) in CSS was proposed in [41]. Different from other techniques, using IM in CSS means multiple chirps are simultaneously transmitted which allows more bits to be embedded in symbols. Consequently, the complexity of receiver design increases as it requires more resources to detect and estimate data bits from a larger signal set. In order to reduce computational complexity, a suboptimal detection algorithm was also proposed to analyze and locate desired data set in a recursive manner.

Although LoRa is a kind of proprietary technique, it mainly refers to the modulation scheme. Developers can implement design or optimization for other layers of OSI models except for physical layers. Essentially, LoRa radio provides wireless link for connecting devices. The medium ccess control (MAC) protocol, which is part of Link Layer, is an important component as it is direactly related to the starting point of communication, which must take various factors into consideration, e.g. the channel state, radio environment, acknowledgement, frequency usage and traffic condition.

As the most well-known LoRa communication based system, LoRaWAN has been adopted worldwide. LoRaWAN defines the use of the ALOHA type medium access control method, which inevitably introduces packet collision or packet loss. Early in 2016, Augustin et al [42] made simulations to study LoRaWAN MAC layer performance. With given settings (100 LoRaWAN end devices, channel bandwidth = 125 kHz, coding rate = 4/5, preamble = 6, payload range [1,58] bytes, packet arrival follows Poisson law), the obtained capacity usage is 18% of the channel capacity, which is chosen to be the pure-ALOHA protocol. Corresponding link load is 0.48 at which around 60% of the packet transmission failed due to collisions. Due to the absence of channel detection algorithms, e.g. CSMA in 802.11 standard, success rate of LoRaWAN MAC layer is very sensitive to the channel load as pure-ALOHA.

Authors in [43] built a mathematical model to describe packet collision and packet loss in a LoRaWAN network consisting of a number of LoRaWAN end devices and a LoRaWAN gateway. Probability of packet collision increases in a LoRaWAN network as the increment of packet payload size or the value of spreading factor. Packet loss has close relationship with duration of LoRaWAN uplink packet and LoRaWAN gateway delay (the packet loss happens when the gateway is sending ACK for preceding uplink LoRaWAN communication). In [44], a packet latency model was built by taking packet collision probability and regulatory duty-cycle requirements into consideration. LoRaWAN works on license free ISM band where radio activity is normally limited by local regulators dedicated to the usage of transmitters. The MAC layer performance evaluation for LoRaWAN should include this limitation as an important factor.

Recently, LoRa has proposed a new modulation technique, i.e. the long-range frequency hopping spread spectrum (LR-FHSS), to further enhance long range capability and improve network capacity. The motivation for developing LR-FHSS is to remove limitations made by duty-cycle regional regulations [45]. Regional regulations strictly define the period a radio can be active on a given channel. The number of terminals and data size for each transmission are also limited, which consequently reduces LoRaWAN network capacity. By the method of frequency hopping, transmission is divided into a number of pieces and each piece is transmitted on different channels. As summarized in [46], LR-FHSS works around limitations by intra-packet hopping to carry longer payload with slow data rate in regions with restrictions on dwell time. Theoretical analysis shows that a 10 dB link budget improvement (about 3 × free-space transmission distance improvement) can be achieved under certain conditions (in the FCC region on the 915 MHz band) [46]. A 140× capacity improvement is possible to be achieved when comparing LR-FHSS with conventional LoRa (SF12) communication [46]. LR-FHSS is compatible with LoRaWAN hardware and networks where only software upgrading is needed. Such changes allow more and more applications previously restricted by LoRa network capacity to achieve significant improvement and consolidate the application market of LoRa in long range low data rate communication.

4. Industry Iot and LoRa

Conventionally industry related systems are isolated from public networks. Since the proposal of the fourth industrial revolution (Industry 4.0), communication, autonomous and decentralized decisions with the aim of increasing industrial efficiency, productivity, safety and transparency have become a new system design purpose [47]. Industrial IoT is a comprehensive topic referring to various disciplines. When it comes to wireless communication, a strict requirement is proposed to the employed radio system: deterministic timing. Data communication in industry systems usually has real-time timeliness requirements since failure of fulfilling the timing requirement may compromise system performance or even cause dangers to human lives [48].

Normal wireless systems utilize the ALOHA-like protocol, or the CSMA-CA algorithm to deal with channel access and to implement interference avoidance. Channel access strategies based on randomness are not applicable in Industry IoT because radio environment in industrial scenarios often suffer from various channel impairments such as path loss, shadowing effect and unpredictable obstacles [49,50]. An idea of achieving deterministic behavior in wireless communication is to bound timing of transmission and receiving within a specified period, i.e. a slot. In [51], authors proposed a modified time slotted channel hoping (TSCH) strategy for the use of the LoRaWAN MAC layer to enable better frequency and code diversity on LoRaWAN end devices and network servers. In the evaluation test, LoRaWAN end devices were allocated with different spreading factors and different channels. Data transmission was not based on random access but started with synchronized signal by which packet conflicts on a channel can be eliminated. This method supports unconfirmed uplink communication only.

To achieve flexible communication in Industrial IoT, authors in [52] proposed a new MAC layer strategy to support real-time data flow over LoRa based networks (RT-LoRa). RT-LoRa works with star topology in which a sink node takes responsibility of synchronizing all end devices using regular beacon signals. End devices consist of two types: the stationary node and mobile node. The stationary node is responsible for collecting sensory data whilst the mobile node is allowed to move in the sensing area. In-network time is organized and bounded by cyclically repeated superframe which mainly consists of beacon, contention access period (CAP) and contention free period (CFP) .

Features of RT-LoRa can be concluded as follows. (1) CAP and CFP contain a number of timeslot sets by which duration of radio activities can be measured and strictly restricted within one or more slots, (2) In CAP, end devices use Slotted-ALOHA based strategies along with randomly generated 3-tuple parameters (the channel, spreading factor and time slot) to compete for channel accessing. The random parameters distribute channel usage by which the success rate of communication increases. (3) In CFP, only end devices allocated in the current time slot is allowed to communicate with the sink node, (4) QoS algorithm is provided in CFP to ensure reliability of communication at levels of normal, reliable and most reliable, (5) Radio channels are carefully allocated in each superframe to fulfill requirements of duty-cycle under different regions.

A similar real-time LoRa protocol was also proposed in [53] to achieve collision-free communication. Timing in a LoRa network is divided into frames and further divided into a number of slots. On this basis, a real-time task scheduling algorithm using logical slot indices is provided to regulate LoRa end device radio communication according to the length of data packet, i.e. transmission time required for communication. With the help of modified Listen-Before-Talk mechanism, the evaluation test confirmed that over 94% packet delivering rate is achievable although high external interferences are present.

In the scenarios of Industrial IoT, LoRa techniques are usually employed to collect data generated on LoRa end devices. Research studies mainly focus on how to ensure timeliness of wireless communication. Normally, communication in industry relies on cable connection (e.g. Ethernet, Field-bus, RS232/485), which has less concern about the interference and latency. Wireless communication usually faces problems of performance degradation as it is easy to be affected by interferences and packet conflicts. The LoRa technique has better performance on interference resistance, but is heavily affected by packet conflicts due to low data rate. Therefore, a proper strategy to optimize wireless latency is quite important and of great needs, if LoRa is to be used in Industrial IoT. In this case, power consumption issue is normally not of the highest priority.

5. Smart City Iot and LoRa

Due to its requirement for massive and large-scale sensor deployment, it is common for smart city IoT to adopt the LoRa technique. Although LoRa has long range communication capability, it has relatively low data rate which affects overall system performance about network capacity, deployment density and power consumption. In [54], authors studied the radio coverage issue of LoRa networks and concluded that (1) it is possible to achieve an 100% packet delivery ratio up to 4 km range and 99% for over 4.8 km under certain conditions. In this case, a LoRaWAN gateway is installed at the height of 30 m above ground, and (2) an empirical path loss model is proposed to determine LoRa link budget at frequency bands of 868 MHz and 433 MHz.

Although LoRa techniques provide desired radio performance for applications of large scale sensor deployment, it is not easy to arrange such deployment as various technical parameters are involved in a LoRa based communication network, e.g. the spreading factor, frequency band, coding rate, distance and obstacle between LoRa end devices and LoRa gateways. In [55], an optimal configuration scheme is provided to allocate appropriate spreading factors and transmission power for every LoRa end device in a LoRaWAN network. The objective of the optimal configuration scheme is to reduce probability of collisions and energy consumption. Two stages are adopted in the scheme. At stage 1, each node tries to be allocated with a proper spreading factor by issuing communication to a gateway using maximum transmission power, and this ensures that the spreading factor later allocated for an end device by the gateway is sufficient to establish a LoRa radio link. At stage 2, the level of transmission power is further optimized for an end device in order to save energy consumption on the premise of the reliable radio link. In [56], a comprehensive study on spreading factor allocation for LoRa based sensor nodes in dense network was studied, where an overall consideration was taken for the use of spreading factors along with directly related parameters, e.g. the payload size, packet error rate, ALOHA mechanism and duty-cycle requirement. Based on the distance between different LoRa end devices and LoRa gateway, a suggestion about spreading factor allocation was given to improve delivery rate of overall network.

In [57], a LoRa-based mesh network was discussed to extend and enhance LoRa network coverage. LoRa radio has long range capability, but is affected by deployment environment. Indoor obstacle can easily stop radio propagation, which is also a common issue for most wireless systems. Mesh networks enable each in-network LoRa device to be a relay node to provide packet forward functionality for neighbor nodes which cannot directly reach a LoRa gateway. A similar idea can be found in [58] where a simplified AODV routing protocol was proposed to organize a LoRa mesh network to cover areas that out the range of a single LoRaWAN gateway. A hierarchy-based energy efficient routing protocol (HBEE) designed for the LoRa mesh network was proposed in [59]. In order to quickly build a network structure, HBEE employs concurrent transmission to spread gateway information through the entire network. Concurrent transmission means multiple LoRa network devices at the same level of a tree network forward data packet using a synchronized way, which greatly reduces possibility of packet collision and minimizes network formation time. Multi-path and multi-channel communication algorithms were used during the data collection stage that further improves final data delivery rate. The experimental results obtained in [59] showed HBEE can achieve packet reception rate of 95.7% and 89.8% during the network formation stage and normal operation stage, respectively.

Smart city IoT makes full use of LoRa capability of configurate radio range such that LoRa end devices located at different positions can reach the sink node (e.g. the LoRa gateway) without modifying modulation schemes, which is normally not applicable in many other technologies. Although the LoRaWAN standard is a successful market example in dealing with large scale sensor deployment, it faces the challenge of wireless packet collision, giving rise to the requirement of reasonable configuration and optimization schemes. Moreover, severe radio environment may affect wireless reception despite the fact that LoRa can achieve long range communication. Ad-hoc based mesh networks can provide flexible deployment options, and are particularly useful in smart city scenarios, see references [60–62].

6. Direct-to-satellite Iot and LoRa

DtS-IoT is a very attractive IoT filed which extremely expands physical world connection from the Earth to the space, and internet access is quite convenient in populated areas. However, DtS-IoT is not achievable at most areas on the Earth. Satellite communication is the only solution to provide global coverage. DtS-IoT is a promising research topic that helps address connectivity issues in certain scenarios, for example, disaster recovery scenarios of earthquakes, tsunamis and flooding [63]. Connectivity between ground networks (devices) and Low-Earth Orbit (LEO) satellites can be achieved in two ways, indirect and direct (as shown in Figure 2 below). For those short range communication systems, a ground based gateway is required to play as a relay to build mutual communication with satellites. For long range wireless systems such as LoRa, it is possible to build direct links which make ground deployment more convenient and cost effective.

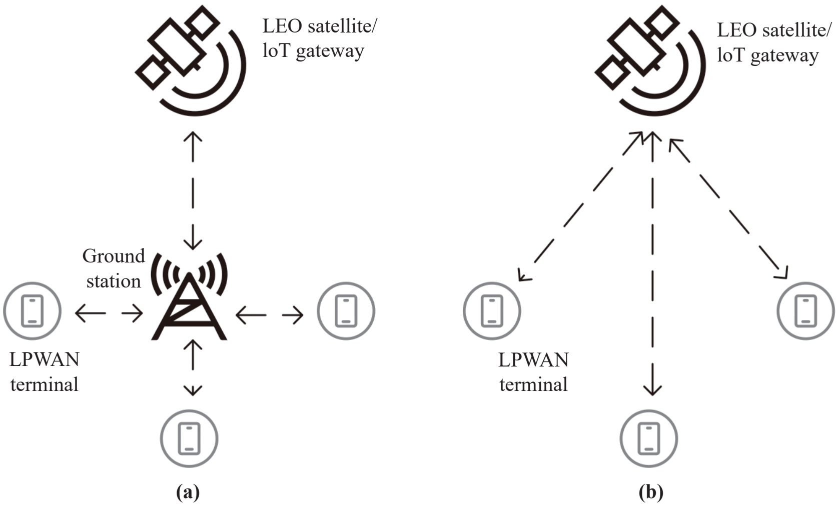

Figure 2. **(a)** Indirect links between ground-based network and LEO satellite; **(b)** Direct links between ground-based network and LEO satellite.

Based on existing LoRaWAN Class B mode, [64] proposed a scheme to utilize LEO satellites as LoRaWAN beacon gateways to keep DtS-IoT connectivity. A LoRaWAN end device working with Class B mode keeps tracking beacon signals sent from LEO satellites and executing Ping-Response tasks as required, see Figure 3.

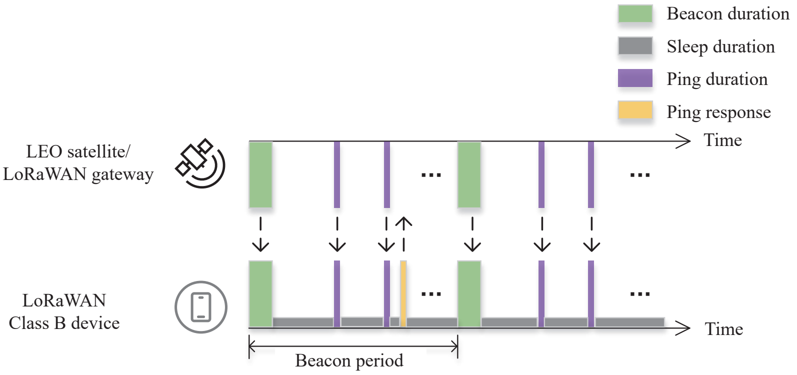

Figure 3. Work flow of DtS (Direct-To-Satellite) with LoRaWAN (LoRa wide area network) Class B device.

When LEO satellites moving around the Earth, if a satellite is out of range of LoRaWAN end device, the end device will adjust the beacon detection window until next beacon from next satellite is captured. In [65], impact of ionospheric scintillation was comprehensively studied to evaluate the limitations of LoRa communication in the use of space-to-Earth satellite communications, while in [66] a trajectory-based LoRa radio uplink transmission policy was studied to improve the success rate of direct connection from the LoRa end device to the satellite in space. The policy takes various factors into consideration, e.g. the received signal strength indicator (RSSI) of LoRa beacons from satellites, frequency shift of beacons (to determine the speed of satellite), and orbital parameters. The result obtained from the analysis of these factors can be used for different transmission policies: plain trajectory, trajectory random, trajectory skip and trajectory random. As authors stated, the proposed policy can at least duplicate the network scalability compared with conventional LoRa communication methods.

LoRa techniques used in space-ground communication are still in a pre-research stage but with very attractive vision [67]. Successful links established between LoRa devices and satellites can make IoT globe coverage cost effective by removing ground station usage. However, there is a long way before this solution becomes mature as extreme long range communication introduces research challenges in areas of modulation technique, antenna design, signal processing, data coding, power management, uplink and downlink policies, interaction between satellites, etc. [68−71].

7. Healthcare Iot and LoRa

Applications related to healthcare IoT are dedicated to the improvement of health care services and life quality in social networks. Conventionally data collection for healthcare requires manual operations where service staffs need to work with service receivers in a face-to-face manner. The LPWAN technology based wireless communication changes the service pattern by enabling data capture to be completed automatically and remotely even the service receivers are in a mobile state. Long range and low power LoRa is an appropriate technique to address numerous connectivity issues between doctors and patients in urban areas and portions of rural areas [72]. Authors in [72] proposed an architecture integrated with the LoRa technique fog computation and satellite connectivity to construct a healthcare service platform with the corresponding system diagram illustrated in Figure 4.

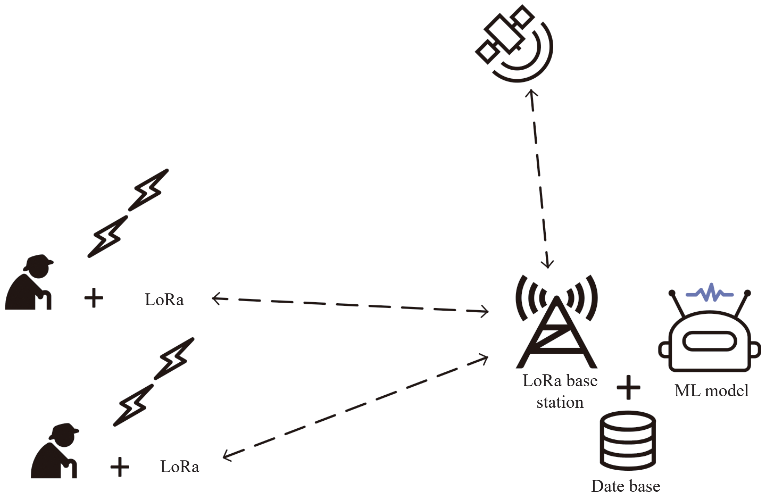

Figure 4. System architecture for rural area network for healthcare IoT.

When sensor devices are activated from the sleep mode, the collected sensory data is sent to the always-on LoRa gateway for processing by fog computing based machine learning models. As conventional Internet connection might be unavailable in rural areas, Low Earth Orbit Satellite connectivity can be employed to connect the local system to the Internet by which doctors from anywhere of the world are able to keep monitoring on status of patients.

In [73] a hybrid and edge based healthcare system was proposed where wearable sensor were equipped on the human body to take responsibility of monitoring health state and reporting to central system. The reporting can experience either of two communication paths, i.e. LoRa or Bluetooth, depending on the distance between sensors and gateways. If a Bluetooth router is within effective range, health data will be sent to router and then forwarded to an edge gateway. Otherwise, the LoRa radio link will be used to convey data to the edge gateway since LoRa can support larger coverage than Bluetooth. The edge gateway is in charge of implementing data processing and making quick responses to situations. Functionalities such as data storage and data analysis are implemented later by a remote cloud server. By combining short-range and long-range wireless communication technologies, data collection in a hybrid system is more feasible and configurable. The system architecture is illustrated in Figure 5:

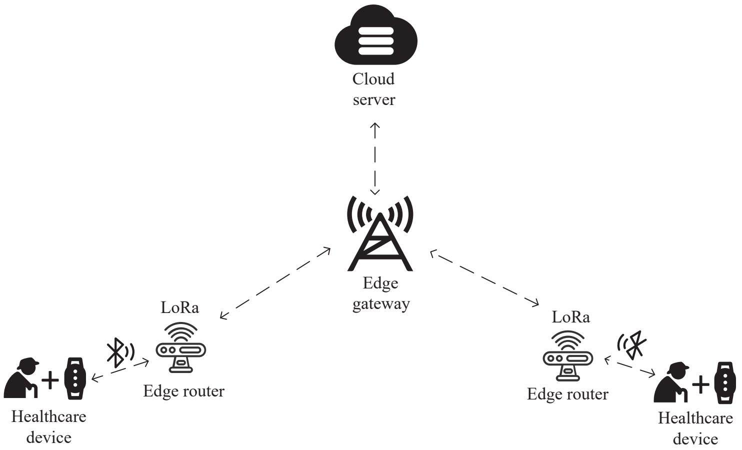

Figure 5. System architecture of hybrid healthcare IoT system.

Adoption of LoRa in Healtcare IoT is an example of taking LoRa as a complementary technique to improve user experience. Different from IoT fields such as smart city IoT and DtS-IoT, LoRa is not the major choice in healthcare IoT, but can be an ideal solution for upgrading existing systems in order to provide better service.

8. Possible Future Development of LoRa

IoT is becoming more and more complicated compared with its initial version. Having devices complete tasks of reporting sensory data and controlling actuators is an important part of IoT. However, the way of system organization and the pattern of network operation are more and more diverse, due to expansion of application fields which require advanced IoT technologies to improve existing systems, or build new systems for certain targets (e.g. communication between low power ground-based devices and satellites). This motivates IoT to move deeply into application scenarios to construct reasonable and efficient systems. In the meantime, technologies adopted in different IoT application scenarios keep developing in different aspects, including new algorithms, system optimization, and system integration. As a kind of low power wireless technologies, LoRa is usually taken by IoT applications to achieve long range communication, which means that effectively integrating LoRa into different systems is one promising future research direction in the development of LoRa. Possible topics on these issues may include but not limited to: 5G network and LoRa, edge computing and LoRa.

8.1. 5G and LoRa

5G network is becoming more and more popular due to its exciting features of massive machine-type communication (mMTC) supporting 1 million devices/km^2, enhanced mobile broadband (eMBB) supporting less than 4 ms latency, and ultra-reliable, low-latency communication (URLLC) supporting mission critical applications with less than 0.5 ms latency [74]. In Industry 4.0 and its later version, mMTC and URLLC are often mentioned as 5G offers significant performance improvement compared with conventional wireless access techniques (e.g. 3G/4G). Traditional industry applications adopt cabling systems to achieve reliable and low latency communication, which has urgent requirements for wireless solutions. Applications such as real-time monitoring, industry-robotics, and remote communication support require highly reliable and low latency wireless technologies to provide most convenience when deploying system [75]. Combining the LoRa and 5G based gateway will be a focus of research. A random-based MAC protocol is not suitable for LoRa to be used in these cases. A systematic re-design is needed for LoRa to cooperate with 5G to achieve precise control by eliminating any uncertainty caused by interference or collisions. For example, the concept of time sensitivity networking (TSN) over 5G has been proposed to enable reliable and deterministic wireless communications between end devices and 5G networks [76−78]. The development of LoRa can be taken as a reference to design TSN-like algorithms in order to make proper arrangement for (1) scheduling priority-based uplink traffic, (2) ensuring downlink control signaling, and (3) managing network scalability.

8.2. Edge Computing and LoRa

Edge computing is a familiar topic to researchers for the reason of rapid growth of IoT applications requiring quick responses to the generated data, such as Vehicular Data Analytics, Smart Home, Video Stream Analytics and Virtual Reality [79]. Conventionally cloud based computing is used to process information collected from different locations, but has limitations in providing real-time responses for safety-critical and performance-sensitivity applications due to unpredictable latency [80]. Edge computing proposes a new computing paradigm by migrating data computation or storage to the network "edge" in order to mitigate the escalation in resource congestion at the central computing unit [81]. In such a paradigm, an edge node is expected to not only exchange data between the local network and the remote center, but also have capability on processing data received via multiple interfaces at the local side. Many studies about LoRa related edge computing can be found from [82−87] that cover fields of medical care, agriculture, block-chain, smart metering, smart city, artificial intelligence, etc. Note that LoRa can also be used in any possible scenarios by cooperating with different hardware/algorithms. For example, in [86] authors proposed a system integrated with edge/fog computing, where LoRa and deep learning algorithms were used to perform fall detection. And overcome the lack of network infrastructures at certain areas. In [87] LoRa and Bluetooth worked together to build a low power smart city network (as shown in Figure 6) designed for collecting daily information such as transportation state, health data, etc. The data is generated and sent to the LoRa edge gateway via short range Bluetooth, and then forwarded to the LoRa fog gateway via long range LoRa links. On the LoRa edge and fog gateway, preliminary data processing will be implemented by which corresponding responses can be made at the local side and the volume of data delivered to the Cloud can be minimized. A combination of LoRaWAN and Wi-Fi/Ethernet was proposed in [88] to build an autonomous server which can process and store data even in the absence of internet connectivity.

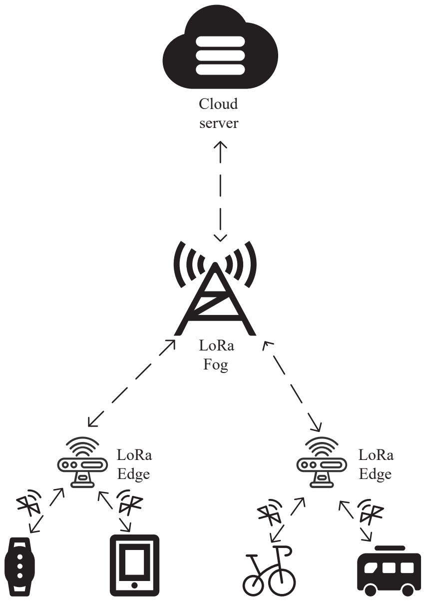

Figure 6. A hybrid LoRa and Bluetooth city network.

It can be concluded that LoRa is quite popular as a data communication technique in many different edge computing-based applications. However, as a pure physical layer communication technique, LoRa is in short of architecture design to support diverse application requirements. An example solution is the LoRaWAN standard, but such a strandard is insufficient as the deign purpose of LoRaWAN is for reporting data, rather than supporting local data processing. In the future development, relevant research is needed to find out how to properly deploy and allocate LoRa resource in the context of edge computing.

In general, it is reasonable to believe, there are two future promising development directions in LoRa, i.e. (1) enhancement of LoRa communication efficiency, and (2) design of interaction mechanisms between LoRa and other technologies/systems, where the enhancement on communication efficiency could be treated as a vertical development direction. As a bottom communication technology, LoRa is often used to collect massively distributed device data. Having data transmission deterministic and reliable is an important research topic in promoting LoRa for the use of dense networks. Making LoRa collaborative could be treated as a horizontal development direction, where the LoRa technique is expected to work together with different systems through proper integration.

9. Conclusions

Rapid development of IoT makes more and more application fields adopt LoRa to establish close links between IoT objects and data processing systems. As one of LPWAN technologies, LoRa is particularly useful for networking embedded and low-cost devices deployed in a wide area. As per characteristics of different IoT fields, the use of LoRa technique may have different emphasis. In industry IoT like fields, interference robustness of LoRa along with the specifically designed strategy for ensuring deterministic timing is the main point, which provides a reliable wireless communication link for industrial applications. For smart city IoT like fields, flexible radio configuration which allows massive and large scale network deployment is the benefit brought by the LoRa technique. However, network performance evaluation and optimization algorithms are needed to help LoRa based network to resolve packet conflict issues. DtS-IoT is a new area that makes use of long range communication capability to its maximum performance. Challenges in this case require more study as existing research made for the LoRa technique may be insufficient. Healthcare IoT like fields demonstrate the use of the LoRa technique in associating with other systems or techniques to improve service quality. In general, the LoRa technique is particularly important in building communication links for ubiquitous computing of IoT. Researches on further improving communication range and interference resistance could become major focuses as they are the core factors of the LoRa technique. In the future development, the LoRa technique can evolve towards directions of (1) efficient communication for stronger precise control capability, and (2) reasonable mechanism for better interaction with other systems.

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References

1. Elijah, O.; Rahman, T. A.; Orikumhi, I.; *et al*, An overview of internet of things (IoT) and data analytics in agriculture: Benefits and challenges. *IEEE Internet Things J.*, **2018**, *5*: 3758−3773.
2. A shton, K. That ' Internet of Things' Things. RFID Journal, 2009. Available online: http://www.itrco.jp/libraries/RFIDjournal-That%20Internet%20of%20Things%20Thing.pdf. (accessed on 5 November 2022).
3. Serials Y: Global Information Infrastructure, Internet Protocol Aspects, and Next-Generation Networks. Recommendation ITU-Y Y. 2060, 2012. Available online: https://kipdf.com/series-y-global-information-infrastructure-internet-protocol-aspects-and-next-ge_5ae57e537f8b9ad98a8b4649.html. (accessed on 10 November 2022).
4. SEMTECH. Real-world LoRaWAN^{TM} Network Capacity for Electrical Metering Applications. Semtech White Paper, 2017.Available online: https://cdn2.hubspot.net/hubfs/2507363/Semtech_Network_Capacity_White_Paper.pdf. (accessed on 10 November 2022).
5. de Castro Tomé, M.; Nardelli, P.H.J.; Alves, H, Long-range low-power wireless networks and sampling strategies in electricity metering. *IEEE Trans. Ind. Electron.*, **2019**, *66*: 1629−1637.
6. Magrin, D.; Centenaro, M.; Vangelista, L. Performance evaluation of LoRa networks in a smart city scenario. In *2017 IEEE International Conference on Communications (ICC)*, *Paris*, *France*, *21–25 May 2017*; IEEE: Paris, 2017; pp. 1–7. doi:10.1109/ICC.2017.7996384
7. Huang, P.; Xiao, L.; Soltani, S.; *et al*, The evolution of MAC protocols in wireless sensor networks: A survey. *IEEE Commun. Surv. Tutorials*, **2013**, *15*: 101−120.
8. Raza, U.; Kulkarni, P.; Sooriyabandara, M, Low power wide area networks: An overview. *IEEE Commun. Surv. Tutorials*, **2017**, *19*: 855−873.
9. Farrell, S. Low-Power Wide Area Network (LPWAN) Overview. Internet Engineering Task Force (IETF), 2018. Available online: https://www.rfc-editor.org/rfc/rfc8376.
10. Tikhvinsky, V. LPWAN Narrowband Technologies (LoRaWAN, SigFox, etc.) for M2M Networks and Internet of Things Design. ITU Regional Forum on "Internet of Things, Telecommunication Networks and Big Data as basic infrastructure for Digital Economy". Russia: Saint-Petersburg, 2018. Available online: https://www.itu.int/en/ITU-T/Workshops-and-Seminars/20180604/Documents/V_Tikhvinskiy.pdf (accessed on 8 November 2022).
11. ROHM. The Latest Technology Trends of Wi-SUN Wireless Communication Modules. ROHM Semiconductor, White Paper, 2021. Available online: https://fscdn.rohm.com/en/products/databook/white_paper/module/power_module/specified_low_power/wi-sun-han1_wp-e.pdf (accessed on 7 November 2022).
12. Sinha, R.S.; Wei, Y.Q.; Hwang, S.H, A survey on LPWA technology: LoRa and NB-IoT. *ICT Express*, **2017**, *3*: 14−21.
13. Sun, Z.H.; Yang, H.Q.; Liu, K.; *et al*, Recent advances in LoRa: A comprehensive survey. *ACM Trans. Sens. Netw.*, **2022**, *18*: 67.
14. Gkotsiopoulos, P.; Zorbas, D.; Douligeris, C, Performance determinants in LoRa networks: A literature review. *IEEE Commun. Surv. Tutorials*, **2021**, *23*: 1721−1758.
15. Li, C. N.; Cao, Z.C, LoRa networking techniques for large-scale and long-term IoT: A down-to-top survey. *ACM Comput. Surv.*, **2023**, *55*: 52.
16. Sharma, N.; Shamkuwar, M.; Singh, I. The history, present and future with IoT. In *Internet of Things and Big Data Analytics for Smart Generation*; Balas, V. ; Solanki, V. ; Kumar, R. ; *et al*, Eds. ; Springer: Cham, 2019; pp. 27–51. doi:10.1007/978-3-030-04203-5_3
17. Goudos, S. K.; Dallas, P. I.; Chatziefthymiou, S.; *et al*, A survey of IoT key enabling and future technologies: 5G, mobile IoT, sematic web and applications. *Wireless Pers. Commun.*, **2017**, *97*: 1645−1675.
18. Savaglio, C.; Ganzha, M.; Paprzycki, M.; *et al*, Agent-based internet of things: State-of-the-art and research challenges. *Future Gener. Comput. Syst.*, **2020**, *102*: 1038−1053.
19. Glaroudis, D.; Iossifides, A.; Chatzimisios, P, Survey, comparison and research challenges of IoT application protocols for smart farming. *Comput. Netw.*, **2020**, *168*: 107037.
20. Mekki, K.; Bajic, E.; Chaxel, F.; *et al*, A comparative study of LPWAN technologies for large-scale IoT deployment. *ICT Express*, **2019**, *5*: 1−7.
21. Adelantado, F.; Vilajosana, X.; Tuset-Peiro, P.; *et al*, Understanding the limits of LoRaWAN. *IEEE Commun. Mag.*, **2017**, *55*: 34−40.
22. Devalal, S.; Karthikeyan, A. LoRa technology-an overview. In *2018 Second International Conference on Electronics*, *Communication and Aerospace Technology (ICECA)*, *Coimbatore*, *India*, *29–31 March 2018*; IEEE: Coimbatore, 2018; pp. 284–290. doi:10.1109/ICECA.2018.8474715
23. Chaudhari, B. S.; Zennaro, M.; Borkar, S, LPWAN technologies: Emerging application characteristics, requirements, and design considerations. *Future Internet*, **2020**, *12*: 46.
24. Perwej, Y.; Haq, K.; Parwej, F.; *et al*, The internet of things (IoT) and its application domains. *Int. J. Comput. Appl.*, **2019**, *182*: 36−49.
25. LoRa. Platform for IoT. Available online: https://www.semtech.com/lora/. (accessed on 15 November 2022).
26. Semtech Corporation. LoRa® and LoRaWAN®: A Technical Overview. Technical Paper, 2020. Available online: https://lora-developers.semtech.com/uploads/documents/files/LoRa_and_LoRaWAN-A_Tech_Overview-Downloadable.pdf (accessed on 13 November 2022).

27. Lavric, A.; Petrariu, A.I. LoRaWAN communication protocol: The new era of IoT. In *2018 International Conference on Development and Application Systems (DAS)*, *Suceava*, *Romania*, *24– 26 May 2018*; IEEE: Suceava, 2018; pp. 74 –77. doi:10.1109/DAAS.2018.8396074
28. Jouhari, M.; Amhoud, E.M.; Saeed, N.; *et al*. A survey on scalable LoRaWAN for massive IoT: Recent advances, potentials, and challenges. arXiv preprint arXiv: 2202.11082, 2022. Available online: https://arxiv.org/pdf/2202.11082.pdf (accessed on 13 November 2022).
29. Siddique, A.; Prabhu, B.; Chaskar, A.; *et al*, A review on intelligent agriculture service platform with LoRa based wireless sensor network. *Int. Res. J. Eng. Technol.*, **2019**, *6*: 2539−2542.
30. Vejlgaard, B.; Lauridsen, M.; Nguyen, H.; *et al*. Coverage and capacity analysis of Sigfox, LoRa, GPRS, and NB-IoT. In *2017 IEEE 85th Vehicular Technology Conference (VTC Spring)*, *Sydney*, *NSW*, *Australia*, *04–07 June 2017*; IEEE: Sydney, 2017; pp. 1–5. doi:10.1109/VTCSpring.2017.8108666
31. Naik, N. LPWAN technologies for IoT systems: Choice between ultra narrow band and spread spectrum. In *2018 IEEE International Systems Engineering Symposium (ISSE)*, *Rome*, *Italy*, *01 –03 October 2018*; IEEE: Rome, 2018; pp. 1 –8. doi:10.1109/SysEng.2018.8544414
32. Tsotsolas, N.; Komisopoulos, F.; Papadopoulos, P.; *et al*. An integrated LoRa-based IoT platform serving smart farming and agrologistics. *Emerging Ecosystem-Centric Business Models for Sustainable Value Creation*. IGI Global, **2022**: 132−158.
33. SEMTECH. SX1276/77/78/79 –137 MHz to 1020 MHz Low Power Long Range Transceiver. 2020. Available online: https://www.mouser.com/datasheet/2/761/sx1276-1278113.pdf (accessed on 4 November 2022).
34. Petäjäjärvi, J.; Mikhaylov, K.; Pettissalo, M.; *et al*. Performance of a low-power wide-area network based on LoRa technology: Doppler robustness, scalability, and coverage. *Int. J. Distrib. Sens. Netw*. **2017**, in press. doi:10.1177/1550147717699412
35. Mroue, H.; Nasser, A.; Parrein, B.; *et al*. Analytical and simulation study for LoRa modulation. In *2018 25th International Conference on Telecommunications (ICT)*, *Saint-Malo*, *France*, *26–28 June 2018*; IEEE: Saint-Malo, 2018; pp. 655 –659. doi:10.1109/ICT.2018.8464879
36. Pasolini, G, On the LoRa chirp spread spectrum modulation: Signal properties and their impact on transmitter and receiver architectures. *IEEE Trans. Wireless Commun.*, **2022**, *21*: 357−369.
37. Croce, D.; Gucciardo, M.; Mangione, S.; *et al*, Impact of LoRa imperfect orthogonality: Analysis of link-level performance. *IEEE Commun. Lett.*, **2018**, *22*: 796−799.
38. Semtech Corporation. LoRa Modulation Basics. 2015.
39. Nguyen, T.T.; Nguyen, H.H.; Barton, R.; *et al*, Efficient design of chirp spread spectrum modulation for low-power wide-area networks. *IEEE Internet Things J.*, **2019**, *6*: 9503−9515.
40. de Almeida, I.B.F.; Chafii, M.; Nimr, A.; *et al*, Alternative chirp spread spectrum techniques for LPWANs. *IEEE Trans. Green Commun. Netw.*, **2021**, *5*: 1846−1855.
41. Hanif, M.; Nguyen, H.H, Frequency-shift chirp spread spectrum communications with index modulation. *IEEE Internet Things J.*, **2021**, *8*: 17611−17621.
42. Augustin, A.; Yi, J. Z.; Clausen, T.; *et al*, A study of LoRa: Long range & low power networks for the internet of things. *Sensors*, **2016**, *16*: 1466.
43. Ferre, G. Collision and packet loss analysis in a LoRaWAN network. In *2017 25th European Signal Processing Conference (EUSIPCO)*, *Kos*, *Greece*, *28 August 2017 –02 September 2017*; IEEE: Kos, 2017; pp. 2586 –2590. doi:10.23919/EUSIPCO.2017.8081678
44. Sørensen, R.B.; Kim, D.M.; Nielsen, J.J.; *et al*, Analysis of latency and MAC-layer performance for class a LoRaWAN. *IEEE Wireless Commun. Lett.*, **2017**, *6*: 566−569.
45. Boquet, G.; Tuset-Peiró, P.; Adelantado, F.; *et al*, LR-FHSS: Overview and performance analysis. *IEEE Commun. Mag.*, **2020**, *59*: 30−36.
46. Semtech. Application note: LR-FHSS system performance. Available online:https://lora-developers.semtech.com/library/product-documents/. (accessed on 8 October 2022).
47. Boyes, H.; Hallaq, B.; Cunningham, J.; *et al*, The industrial internet of things (IIoT): An analysis framework. *Comput. Ind.*, **2018**, *101*: 1−12.
48. Bartolomeu, P.; Alam, M.; Ferreira, J.; *et al*, Supporting deterministic wireless communications in industrial IoT. *IEEE Trans. Ind. Inf.*, **2018**, *14*: 4045−4054.
49. Wang, W.B.; Capitaneanu, S.L.; Marinca, D.; *et al*, Comparative analysis of channel models for industrial IoT wireless communication. *IEEE Access*, **2019**, *7*: 91627−91640.
50. Foukalas, F.; Pop, P.; Theoleyre, F.; *et al*. Dependable wireless industrial IoT networks: Recent advances and open challenges. In *2019 IEEE European Test Symposium (ETS)*, *Baden-Baden*, *Germany*, *27– 31 May 2019*; IEEE: Baden-Baden, 2019; pp. 1 –10. doi:10.1109/ETS.2019.8791551
51. Rizzi, M.; Ferrari, P.; Flammini, A.; *et al*. Using LoRa for industrial wireless networks. In *2017 IEEE 13th International Workshop on Factory Communication Systems (WFCS)*, *Trondheim*, *Norway*, *31 May 2017–02 June 2017*; IEEE: Trondheim, 2017; pp. 1–4. doi:10.1109/WFCS.2017.7991972
52. Leonardi, L.; Battaglia, F.; Lo Bello, L, RT-LoRa: A medium access strategy to support real-time flows over LoRa-based networks for industrial IoT applications. *IEEE Internet Things J.*, **2019**, *6*: 10812−10823.
53. Hoang, Q.L.; Jung, W.S.; Yoon, T.; *et al*, A real-time LoRa protocol for industrial monitoring and control systems. *IEEE Access*, **2020**, *8*: 44727−44738.
54. Jörke, P.; Böcker, S.; Liedmann, F.; *et al*. Urban channel models for smart city IoT-networks based on empirical measurements of LoRa-links at 433 and 868 MHz. In *2017 IEEE 28th Annual International Symposium on Personal*, *Indoor*, *and Mobile Radio Communications (PIMRC)*, *Montreal*, *QC*, *Canada*, *08–13 October 2017*; IEEE: Montreal, 2017; pp. 1–6. doi:10.1109/PIMRC.2017.8292708
55. Premsankar, G.; Ghaddar, B.; Slabicki, M.; *et al*, Optimal configuration of LoRa networks in smart cities. *IEEE Trans. Ind. Inf.*, **2020**, *16*: 7243−7254.
56. Lavric, A, LoRa (long-range) high-density sensors for internet of things. *J. Sens.*, **2019**, *2019*: 3502987.
57. Lee, H.C.; Ke, K.H, Monitoring of large-area IoT sensors using a LoRa wireless mesh network system: Design and evaluation. *IEEE Trans. Instrum. Meas.*, **2018**, *67*: 2177−2187.
58. Almeida, N.C.; Rolle, R.P.; Godoy, E.P.; *et al*. Proposal of a hybrid LoRa Mesh/LoRaWAN network. In *2020 IEEE International Workshop on Metrology for Industry 4. 0 & IoT*, *Roma*, *Italy*, *03–05 June 2020*; IEEE: Roma, 2020; pp. 702 –707.

doi:10.1109/MetroInd4.0IoT48571.2020.9138206

59. Hong, S. G.; Yao, F.; Ding, Y. L.; *et al*, A hierarchy-based energy-efficient routing protocol for LoRa-mesh network. *IEEE Internet Things J.*, **2022**, *9*: 22836−22849.
60. Huh, H.; Kim, J.Y. LoRa-based mesh network for IoT applications. In *2019 IEEE 5th World Forum on Internet of Things (WF-IoT)*, *Limerick*, *Ireland*, *15–18 April 2019*; IEEE: Limerick, 2019; pp. 524–527. doi:10.1109/WF-IoT.2019.8767242
61. Osorio, A.; Calle, M.; Soto, J. D.; *et al*, Routing in LoRaWAN: Overview and challenges. *IEEE Commun. Mag.*, **2020**, *58*: 72−76.
62. Centelles, R. P.; Freitag, F.; Meseguer, R.; *et al*, Beyond the star of stars: An introduction to multihop and mesh for LoRa and LoRaWAN. *IEEE Pervas. Comput.*, **2021**, *20*: 63−72.
63. Fraire, J.A.; Céspedes, S.; Accettura, N. Direct-to-satellite IoT - a survey of the state of the art and future research perspectives. In *18th International Conference on Ad-Hoc Networks and Wireless on Ad-Hoc*, *Mobile*, *and Wireless Networks*, *Luxembourg*, *Luxembourg*, *October 1–3*, *2019*; Springer: Luxembourg, 2019; pp. 241–258. doi:10.1007/978-3-030-31831-4_17
64. Fraire, J.A.; Henn, S.; Dovis, F.; *et al*. Sparse satellite constellation design for LoRa-based direct-to-satellite internet of things. In *GLOBECOM 2020 - 2020 IEEE Global Communications Conference*, *Taipei*, *China*, *07–11 December 2020*; IEEE: Taipei, China, 2020; pp. 1–6. doi:10.1109/GLOBECOM42002.2020.9348042
65. Fernandez, L.; Ruiz-De-Azua, J. A.; Calveras, A.; *et al*, Assessing LoRa for satellite-to-earth communications considering the impact of ionospheric scintillation. *IEEE Access*, **2020**, *8*: 165570−165582.
66. Álvarez, G.; Fraire, J. A.; Hassan, K. A.; *et al*, Uplink transmission policies for LoRa-based direct-to-satellite IoT. *IEEE Access*, **2022**, *10*: 72687−72701.
67. Satellite Based LoRa Unlocks Europe-Wide IoT. White Paper, EchoStar Mobile. Available online: https://www.echostarmobile.com/wp-content/uploads/2022/04/EchoStar_Mobile_White_Paper_compressed.pdf (accessed on 5 November 2022).
68. Ullah, M. A.; Mikhaylov, K.; Alves, H, Analysis and simulation of LoRaWAN LR-FHSS for direct-to-satellite scenario. *IEEE Wireless Commun. Lett.*, **2022**, *11*: 548−552.
69. Chaari, L.; Fourati, M.; Rezgui, J. Heterogeneous LoRaWAN & LEO satellites networks concepts, architectures and future directions. In *2019 Global Information Infrastructure and Networking Symposium (GIIS)*, *Paris*, *France*, *18–20 December 2019*; IEEE: Paris, 2019; pp. 1–6. doi:10.1109/GIIS48668.2019.9044966
70. Doroshkin, A. A.; Zadorozhny, A. M.; Kus, O. N.; *et al*, Experimental study of LoRa modulation immunity to Doppler effect in CubeSat radio communications. *IEEE Access*, **2019**, *7*: 75721−75731.
71. Colavolpe, G.; Foggi, T.; Ricciulli, M.; *et al*, Reception of LoRa signals from LEO satellites. *IEEE Trans. Aerosp. Electron. Syst.*, **2019**, *55*: 3587−3602.
72. Dimitrievski, A.; Filiposka, S.; Melero, F.J.; *et al*, Rural healthcare IoT architecture based on low-energy LoRa. *Int. J. Environ. Res. Public Health*, **2021**, *18*: 7660.
73. Wu, F.; Qiu, C.K.; Wu, T.Y.; *et al*, Edge-based hybrid system implementation for long-range safety and healthcare IoT applications. *IEEE Internet Things J.*, **2021**, *8*: 9970−9980.
74. Adebusola, J.A.; Ariyo, A.A.; Elisha, O.A.; *et al*. An overview of 5G technology. In *2020 International Conference in Mathematics*, *Computer Engineering and Computer Science (ICMCECS)*, *Ayobo*, *Nigeria*, *18–21 March 2020*; IEEE: Ayobo, 2020; pp. 1–4. doi:10.1109/ICMCECS47690.2020.240853
75. Rao, V.C.S.; Kumarswamy, P.; Phridviraj, M.S.B.; *et al*. 5G enabled industrial internet of things (IIoT) architecture for smart manufacturing. In *Data Engineering and Communication Technology*; Reddy, K.A.; Devi, B.R.; George, B.; *et al*, Eds.; Springer: Singapore, 2021; pp. 193–201. doi:10.1007/978-981-16-0081-4_20
76. Larrañaga, A.; Lucas-Estañ, M. C.; Martinez, I.; *et al*. Analysis of 5G-TSN integration to support industry 4.0. In *2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, *Vienna*, *Austria*, *08–11 September 2020*; IEEE: Vienna, 2020; pp. 1111–1114. doi:10.1109/ETFA46521.2020.9212141
77. Nasrallah, A.; Thyagaturu, A.S.; Alharbi, Z.; *et al*, Ultra-low latency (ULL) networks: The IEEE TSN and IETF DetNet standards and related 5G ULL research. *IEEE Commun. Surv. Tutorials*, **2019**, *21*: 88−145.
78. Gundall, M.; Huber, C.; Rost, P.; *et al*. Integration of 5G with TSN as prerequisite for a highly flexible future industrial automation: Time synchronization based on IEEE 802.1AS. In *IECON 2020 The 46th Annual Conference of the IEEE Industrial Electronics Society*, *Singapore*, *18–21 October 2020*; IEEE: Singapore, 2020; pp. 3823–3830. doi:10.1109/IECON43393.2020.9254296
79. Liu, F.; Tang, G. M.; Li, Y.; *et al*, A survey on edge computing systems and tools. *Proc. IEEE*, **2019**, *107*: 1537−1562.
80. Sarker, V.K. ; Queralta, J.P.; Gia, T.N.; *et al*. A survey on LoRa for IoT: Integrating edge computing. In: *2019 Fourth International Conference on Fog and Mobile Edge Computing (FMEC)*, *Rome*, *Italy*, *10–13 June 2019*; IEEE: Rome, 2019; pp. 295–300. doi:10.1109/FMEC.2019.8795313
81. Yu, W.; Liang, F.; He, X. F.; *et al*, A survey on the edge computing for the internet of things. *IEEE Access*, **2018**, *6*: 6900−6919.
82. Drăgulinescu, A.M.C.; Manea, A.F.; Fratu, O.; *et al*, LoRa-based medical IoT system architecture and testbed. *Wireless Pers Commun*, **2022**, *126*: 25−47.
83. Gia, T.N.; Qingqing, L.; Queralta, J.P.; *et al*. Edge AI in smart farming IoT: CNNs at the edge and fog computing with LoRa. In *2019 IEEE AFRICON*, *Accra*, *Ghana*, *25–27 September 2019*; IEEE: Accra, 2019; pp. 1–6. doi:10.1109/AFRICON46755.2019.9134049
84. Hou, L.; Zheng, K.; Liu, Z. M.; *et al*, Design and prototype implementation of a blockchain-enabled LoRa system with edge computing. *IEEE Internet Things J.*, **2021**, *8*: 2419−2430.
85. Kumari, P.; Mishra, R.; Gupta, H.P.; *et al*. An energy efficient smart metering system using edge computing in LoRa network. *IEEE Trans*. *Sustainable Comput*. **2021**, in press. doi:10.1109/TSUSC.2021.3049705
86. Queralta, J.P.; Gia, T.N.; Tenhunen, H.; *et al*. Edge-AI in LoRa-based health monitoring: Fall detection system with fog computing and LSTM recurrent neural networks. In *2019 42nd International Conference on Telecommunications and Signal Processing (TSP)*, *Budapest*, *Hungary*, *01–03 July 2019*; IEEE: Budapest, 2019; pp. 601–604. doi:10.1109/TSP.2019.8768883
87. Ferreira, C.M.S.; Oliveira, R.A.R.; Silva, J.S. Low-energy smart cities network with LoRa and Bluetooth. In *2019 7th IEEE International Conference on Mobile Cloud Computing*, *Services*, *and Engineering (MobileCloud)*, *Newark*, *CA*, *USA*, *04–09 April 2019*; IEEE: Newark, 2019; pp. 24–29. doi:10.1109/MobileCloud.2019.00011
88. Barro, P.A.; Zennaro, M.; Pietrosemoli, E. TLTN – The local things network: On the design of a LoRaWAN gateway with autonomous servers for disconnected communities. In *2019 Wireless Days (WD)*, *Manchester*, *UK*, *24–26 April 2019*; IEEE: Manchester, 2019; pp. 1–4. doi:10.1109/WD.2019.8734239

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