Chapter 5
The Internet of Things Narrow-Band LPWAN/UNB Systems

As frequently mentioned already, the concept of the Internet of Things has led to the development of a number of new systems and protocols characterized by a specific set of requirements that neither current cellular systems nor long distance (e.g. WiMAX) nor short term (e.g. Bluetooth, IEEE 802.11g/a/n/ac) were able to meet in full scope. These distinguishing features include, above all, the large coverage achievable through the use of various signal processing methods, resulting in increased processing gain, adaptive transmission rates (from a few hundred b/s to a dozen or so kb/s), radiated power, modulation, duty cycles, etc., so that, at the same time, the connected devices energy consumption could be minimized.

5.1 LoRaWAN (LoRa): Architecture, Radio Interface and Device Classes

'LoRaWAN', an abbreviation standing for long-range WAN, is a long-range open telecommunications system currently supported by the LoRa Alliance. Under the name LoRa, one should understand a closed, proprietary solution for the physical layer of the LoRaWAN (long-range wide area network) system [99, 100], developed by the French company Cycleo (later acquired by Semtech), based on a variation of transmission with a spread spectrum, using a multi-valued CSS method. This means that in contrast to the standard CSS technique described in Sect. 4.1.2, where a single chirp symbol encoded only one bit, the version of this method used in LoRa allows to encode from 7 to 12 bits in a symbol. In principle, the LoR is characterized by a long unattended battery life (about 10 years in favourable conditions), low transmission speeds (up to 22 kbps for SF = 7 and BW = 500 kHz and 50 kbps in the physical layer using FSK modulation) and large ranges (2–5 km in urbanized areas up to 15 km in suburban areas). The system can work, depending on the region of the world, in variously defined ISM bands, in which different rules apply, for

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example, regarding the effective isotropic radiated power (EIRP), duty cycle (DC), an obligatory number and width of channels, the use (or not) of LBT, AFA mechanisms or preamble length, etc. The regional specification of the LoRaWAN system [102] determines the values of these parameters individually for the following bands used in different parts of the world:

- EU 433 MHz ISM Band
- CN 470-510 MHz Band
- China 779-787 MHz ISM Band
- EU 863–870 MHz ISM Band in sub-bands (according to Table 2.7):

  M: 868–868.60 MHz (600 kHz in total), ERP = 25 mW, DC $\leq$ 1%
  P: 869.40–869.65 MHz (250 kHz in total), ERP = 500 mW, DC $\leq$ 10%

- US 902-928 MHz ISM Band
- Australia 915-928 MHz ISM Band
- AS923 MHz ISM Band
- South Korea 920-923 MHz ISM Band

5.1.1 LoRaWAN: System Architecture

LoRaWAN, in addition to the system name, is also the name of its link (medium) access layer and defines the communication mechanism of end devices (Fig. 5.1) with LoRa gateways in the star topology, using the LoRa radio interface. LoRaWAN system architecture consists of the following elements:

- End devices responsible for collecting data from sensors and meters and then – using the LoRa radio interface – passing them on to the gateways.
- Gateways are intermediary devices used for forwarding packets coming from the end devices to a network server through an IP-based backbone, allowing the transfer of large aggregate traffic, using such techniques as Ethernet or cellular networks. Several gateways can operate in a given LoRaWAN network, with the same packets being received by different gateways to increase the reliability of data delivery to the server.
- A network server, responsible for removing duplicate packets, decoding them and generating packets to be sent back to end devices.

Unlike traditional cellular networks, end devices are not linked to any specific gateway through which they could access the network. The gateways are used rather as relays of the link layer, to forward packets between devices and the network server, after adding information about the reception quality. Thus, the end device is logically connected to the network server, responsible for the detection of duplicate packets, selection of the appropriate gateway for the relaying of responses and the generation thereof. From a logical point of view, the gateways themselves are transparent to end devices.

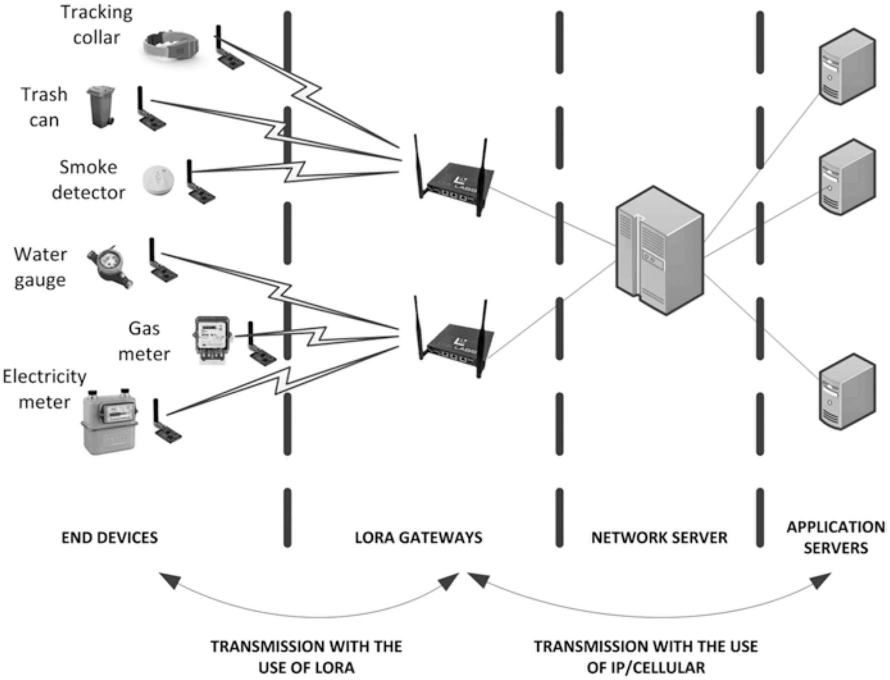


Fig. 5.1 LoRaWAN system topology

5.1.2 LoRaWAN: Device Classes

LoRaWAN defines three classes of end devices (ED), implemented according to the applications for which the ED data was intended. These classes – A, B and C – differ substantially in their work cycle which, in turn, affects their availability (from the point of view of the LoRa gateway) and energy efficiency.

Class A devices – mandatory in all ED's – transmit to the gate only when they have data to send, e.g. after the sensor reading that should be sent. After the transmission is completed, the gateway, which is always in the listening state, gets the opportunity of sending data to the ED twice, after the 'RECEIVE_DELAY1' period and then after the 'RECEIVE_DELAY2' period in the reception windows: 'RX1' and 'RX2', respectively. The end device listens in the second receiving window; however, only when in the first window it has not received any data from the gateway. It then transits to the sleep mode and waits for the data to appear in the transmission buffer from the sensors. Class A, obligatory for all ED in the LoRa system, is at the same time the most energy-efficient but also the least flexible in terms of free communication in both directions (ED ↔ LoRa gateway) due to lack of control from the gateway over the moment of starting its own transmission; the connection initiation is solely the responsibility of the end device, as shown in Fig. 5.2.

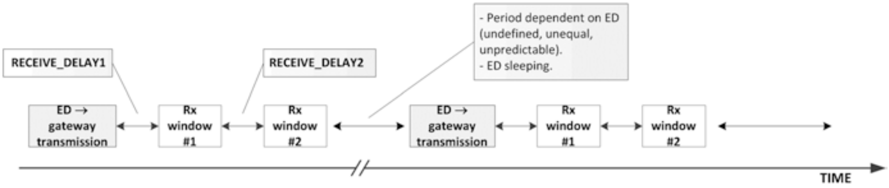


Fig. 5.2 Class A ED operation diagram

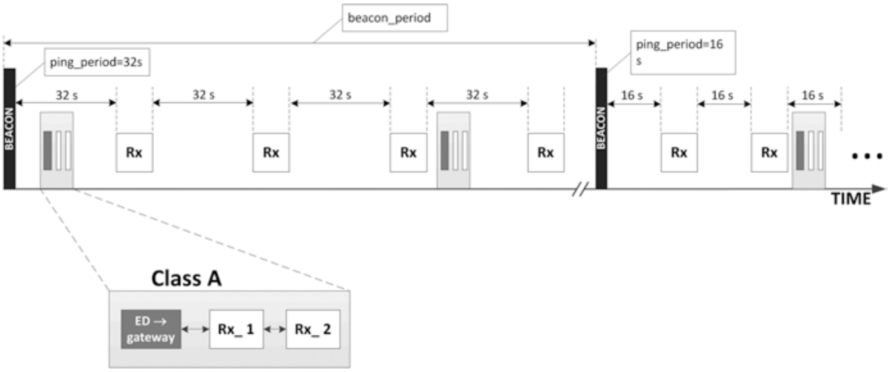


Fig. 5.3 Class B ED operation diagram

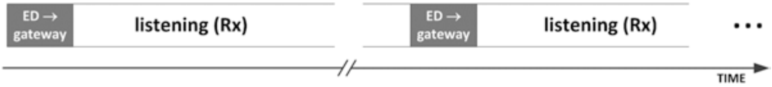


Fig. 5.4 Class C ED operation diagram

Class B of terminal equipment – optional – assumes that, in addition to the implementation of class A (also included in class B), ED will be opening then receiving windows at fixed intervals (‘beacon_interval’), previously determined at the system configuration stage, in order to obtain synchronization with beacons emitted by the LoRa gateway, e.g. every 128 s (as in Fig. 5.3). The most important message carried in the beacons is the information about the listening period (shorter than the ‘beacon_interval’) which sets the ED’s clocks to regular monitoring of transmissions from the LoRa gateway. Such synchronized end devices, parallel to the operation according to the Class A diagram, will regularly switch to the ‘beacon_interval’ listening. This method, due to the increased flexibility of communication between the LoRa gateway and the terminal device, is suitable for applications tolerating certain delays in the reception of messages from end devices, but which require their regular arrival of messages and control over the ED transmission cycle.

Devices belonging to the optional Class C never go into low-energy sleep mode, switching only between the states of transmission and listening (Fig. 5.4). This feature makes it, admittedly, the least energy-efficient but at the same time the most effective one in the context of the LoRa gateway ease of reaching end devices. A typical use scenario for devices of this class has a small tolerance for delays and requires immediate communication with an ED, on demand.

5.1.3 LoRa: Frame Structure, the Most Important Commands

Although LoRa modulation can be used to transmit any frame, the specification [100] determines the physical frame format within which the bandwidth and the spreading factor are held constant. The frame begins the preamble consisting of a series of upchirps, covering the entire width of the BW. In the European band, EU 863–870 MHz ISM Band, it consists of 8 symbols (for Lora modulation) or 5 bytes (for GFSK mode) [102]. The two final signals denote the sync word being a 1-byte value for distinguishing LoR networks using the same frequency ranges. The device, configured for a given word sync word, will stop listening for a particular transmission if the decoded word is different from its own. After the syncword, there are 2.25 downchirps. The appearance of the preamble transmission is depicted in Fig. 5.5 [100, 101]. After the preamble there is a PHDR header with a minimum length of 13 bytes, and a maximum of 28 bytes, optional for the DL, and obligatory for the UL. Its occurrence is called the explicit mode whereas its omission the implicit mode. The latter mode, leading to the reduction of the signalling data in the frame, is selected in situations when the transmission header is not necessary because, e.g. *MACPayload* in Fig. 5.6, coding efficiency *R*, spreading factor *SF* and information about the presence (or absence) of the *PHYPayloadCRC* field are known to both sides of the link (i.e. LEP and LAP) and unchangeable. In the explicit mode, however, regarding UL, there is both a PHDR and a checksum, computed based on the *PHYPayloadCRC* data field, whereas regarding DL, *PHYPayloadCRC* is never included.

The header also has its own cyclic redundancy check (PHDR_CRC) which enables the receiver to detect and reject packets with corrupt headers. The maximum length of the *MACPayload* field of use depends on the region and has been

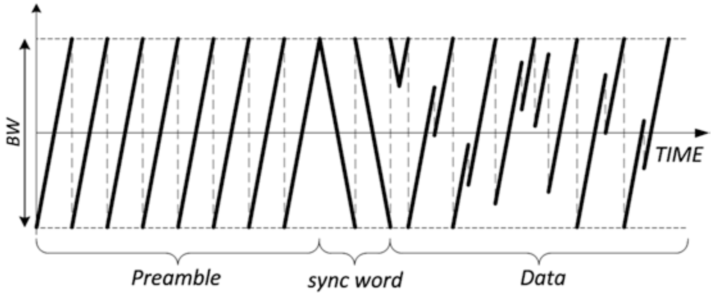


Fig. 5.5 Transmission of the preamble and data in the time and frequency domains

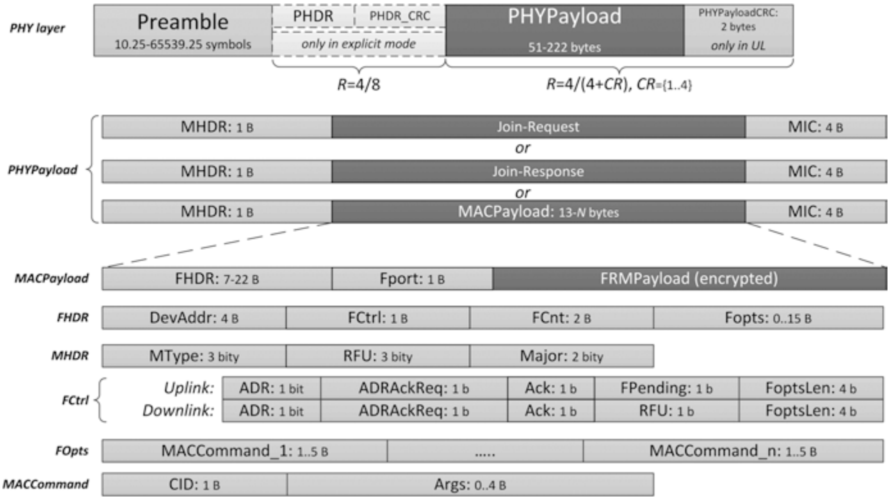


Fig. 5.6 Elements of the physical layer (PHY) frame and link access (MAC) for LoRa

Table 5.1 Maximum MACPayload sizes for EU863-870 bands [100, 102]

Transmission rate DR *(data rate)*	*M*	*N*
0	59	51
1	59	51
2	59	51
3	123	115
4	230 (250[a])	222 (242[a])
5	230 (250[a])	222 (242[a])
6	230 (250[a])	222 (242[a])
7	230 (250[a])	222 (242[a])
8:15	Undefined	

[a] Used with an assumption that the end device will never communicate with the base station via a repeater. Smaller values of M and N in front of the parenthesis are used when it is probable that ED may work with a relay; these values take into account the margin resulting from the possible protocol overhead associated with the encapsulation of packets in the relay

defined in the specification [102] referring to system parameters adapted to the regional specifics of radio spectrum management, as shown in Table 5.1, where the maximum *MACPayload* size without the optional *FOpts* field is *N* and *M* when this field is present in the frame. Even in the absence of user information, the presence of other component fields causes frames to always contain a minimum number of bytes, namely, 13. These fields are as follows: MHDR [1], DevAddr [4], FCtrl [1], FCnt [2], Tport [1] and MIC [4]. *DevAddr* in Fig. 5.6 is a short device address, FPort a field indicating the nature of the data (*FRMPayload*), so its zero value means that this field contains only MAC commands, and its non-zero value indicates that MAC commands are transported in the *FOpts* field. In this case, the value of the *FOptsLen* field is also zero. *FCnt* is a frame counter. The MIC field, on the other hand, is the message integrity code, calculated on the basis of the MHDR, FHDR, FPort fields and the encrypted FRMPayload. *MType* specifies the message type (one of eight), indicating, for example, the message direction (i.e. UL/DL), specifying whether it requires acknowledgement or whether it is a query or acceptance to join the LoRa gateway. *Major* carries information about the LoRaWAN version (currently, the only correct value is zero). *ADR* and *ADRAckReq* fields control the mechanism of the baud rate adaptation by the network server. *ACK* confirms the last received frame. The *FPending* bit, set by the gateway, indicates that there is data in the transmit buffer intended for the end device, requesting opening another receiving window by sending another UL message. *FOptsLen* determines the length of the *FOpts* field in bytes *FOpts* used to transport MAC commands with a maximum total length of 15 octets.

Command identifier (*CID*) identifies a command type. Due to a wide range of radio parameters, such as bandwidth (*BW*), maximum EIRP, duty cycle (*DC*) or occupancy time, the one method of coercing the end device (*ED*) to set these parameters in accordance with regional regulations is by the use of these commands, by means of which the gateway 'tunes' the associated end devices (*ED*). Some of the most vital commands include:

- *CID = 0x02 (LinkCheckReq)*, sent by the end device *ED*, queries the gateway for confirmation of being connected to it. The indicator with the same value (LinkCheckAns), sent back by the gateway as a response to the ED query, contains information about the power level of the signal received from the ED that allows it to assess the link quality.
- *CID = 0x03*, if sent by the gateway *(LinkADRReq)*, means a request to change the baud rate, transmit power, number of repetitions or channel. When sent by an ED (LinkADRAns) means that these changes have been accepted.
- CID = 0x04 identifies the *DutyCycleReq* command specifying the current DC. The terminal device accepts these settings by sending back *DutyCycleAns* command with the same CID.
- CID = 0x06 means *DevStatusReq* command: the gateway asks ED for the battery status and reception quality. ED responds with the *DevStatusAns* command, in which the reception quality determines the so-called margin of demodulation, i.e. the distance between the SNR of the last received message and the minimum SNR needed to receive it properly. In other words, a demodulation margin of 0 dB indicates a reception at the verge of correctness; its higher values, in turn, indicate a certain energy reserve, which increases the assessment of the quality of reception from the ED's point of view.
- CID = 0x09 (*TxParamSetupReq* command) sent by the gateway carries information about the new maximum dwell time and the maximum EIRP allowed by regional regulations, as in Table 5.2. Occupancy time means the maximum period for which ED can transmit continuously (also subject to legal regulations). The end device responds with the same CID indicator, in this case denoting acceptance of the settings (*TxParamSetupAns* command).
- Keep-alive confirmation sent by the terminal device to the gateway.

Table 5.2 Maximum EIRP values established for LoRaWAN system devices [100]

Coded value	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Max EIRP [dBm]	8	10	12	13	14	16	18	20	21	24	26	27	29	30	33	36

The contents of the *FRMPayload* field, before calculating the MIC, must be encrypted. The encryption method is based on the algorithm described in IEEE 802.15.4-2006 specification, Annex B [10] using AES, with a 128-bit key length.

5.1.4 Activation of the End Device

For the end device ED to be able to work in the LoRaWAN network, it must be activated. LoRaWAN defines two ways of activating: over-the-air radio activation (OTAA) and activation by personalization (ABP). As a result of activating the ED, it should obtain the following information:

- Its address (*DevAddr*): a 32-bit identifier of the terminal device, of which 7 bits is used to identify the network, while the remaining 25 bits are the ED network address
- The application identifier (*AppEUI*): the global identifier specified in the EUI64 address space, defining in a unique manner the owner of the terminal device
- The network session key (*NwkSKey*): keys used by the network server and ED to calculate and verify the message integrity code (*MIC*) in order to ensure data integrity
- The application session key (*AppSKey*): the key used by the network server and the end device for encrypting and decrypting the data field in information messages

In the case of OTAA, the connection procedure requires the exchange of ‘join-request’ and ‘join-accept’ messages for each new session. On the basis of the ‘join-accept’ message, the terminal devices then retrieve the session keys (*NwkSkey* and *AppSKey*). During the procedure, these messages, as shown in Fig. 5.6, replace the ‘MACPayload’ field.

In the case of ABP activation, in turn, both session keys are loaded directly to the end devices.

5.1.5 LoRa Physical Layer

The modulation used in the LoRa system (also known as ‘LoR modulation’) is an enhanced, patented ([103]) form of chirp spread spectrum (CSS) described in Sect. 4.1.2. It turns out that, compared to other transmission techniques (e.g. FHSS or DSSS), LoRa is very useful in long-distance IoT systems applications due to its high processing gain, allowing for long-distance work or, in urban environments, over smaller distances (several kilometres) but with effective building penetration.

5.1.5.1 Modulation and Demodulation

In order to be able to encode to $SF = 12$ bits in a single LoRa chirp signal, it is necessary to define a unique frequency trajectory within a single chirp signal for each of the 2^{SF} samples, each lasting $T = BW^{-1}$ [s] and the entire signal duration of $T_s = T \cdot 2^{SF}$ [s]. The modulation effect is achieved by assigning to each symbol a unique shift (offset) of k chips (samples) with respect to the initial frequency f_0, thus encoding the symbol value, or a given modulation state, to that shift. In this way, in order to make space for an m-state modulation, the whole bandwidth $BW = f_F - f_0$ is divided into 2^m equal intervals, each of width $\Delta f = BW \cdot 2^{-m}$, localized at discrete frequencies: $\{f_0 + 0 \cdot \Delta f, f_0 + 1 \cdot \Delta f, f_0 + 2 \cdot \Delta f, \ldots, f_0 + (2^m - 1) \cdot \Delta f\}$. Each of these becomes a starting frequency uniquely associated to one of 2^m binary sequences. A given m-bit long k-th sequence is encoded by initializing (at time T_0) the signal upchirp at a frequency $f_0 + k \cdot \Delta f$, letting it rise (either linearly or exponentially) up to f_F and then abruptly reducing the instantaneous frequency down to f_0 and continuing its incrementation until the end of the chirp that occurs at time T_s.

This method helps obtain multistate modulation (in the range from $2^{SF=7} \div 2^{SF=12}$ states) of the chirp signal, as opposed to the classical, binary form of the chirp modulation (as described in Sect. 4.1.2). Thus, each encoded chirp is a cyclic version of the reference signal, shifted by k chips, as a result of which, the modulated chirp is characterized by a step change in frequency at a position of the k-th chip (sample) of its duration, as shown in Fig. 5.7a for an exemplary shift of $k = 32$ i $SF = 8$.

The chirp $\omega_k^{(SF)}$, modified in relation to its original form given by a formula (24), with the instantaneous frequency being a quadratic function of time (Fig. 5.7a), is now represented by the formula (5.1) [87],where k is the number of shifted chips (offset), while the original chirp signal is cyclically shifted by k chips/samples (Fig. 5.7b).

On the receiving side, the received signal ω_k is multiplied by an unshifted chirp signal by $\omega_{k=0}$. Demodulation of the preamble and synchronization word 'SyncWord', allowing to obtain the time reference necessary for demodulation of the further part of the signal is possible due to the orthogonality feature of the LoRa base signals with the same spreading factor SF. The feature states that the cross-correlation between 2^{SF} possible LoRa base signals with different offsets (m,k) is given by the relationship (5.2). The resultant signal $x_{dem}^{(SF)}$ (given by the formula (5.3) and plotted in Fig. 5.7c) is then subjected to the fast Fourier transform (FFT). The result of this operation is the spectrum with a maximum fringe located at a sample whose index corresponds to the value of the offset k (here equal to 32), which was sought for, as shown in Fig. 5.7. This accomplishes the demodulation process of the chirp. In order to present the complete picture, it should be noted that LoRa orthogonality is also preserved among signals with different SF values,

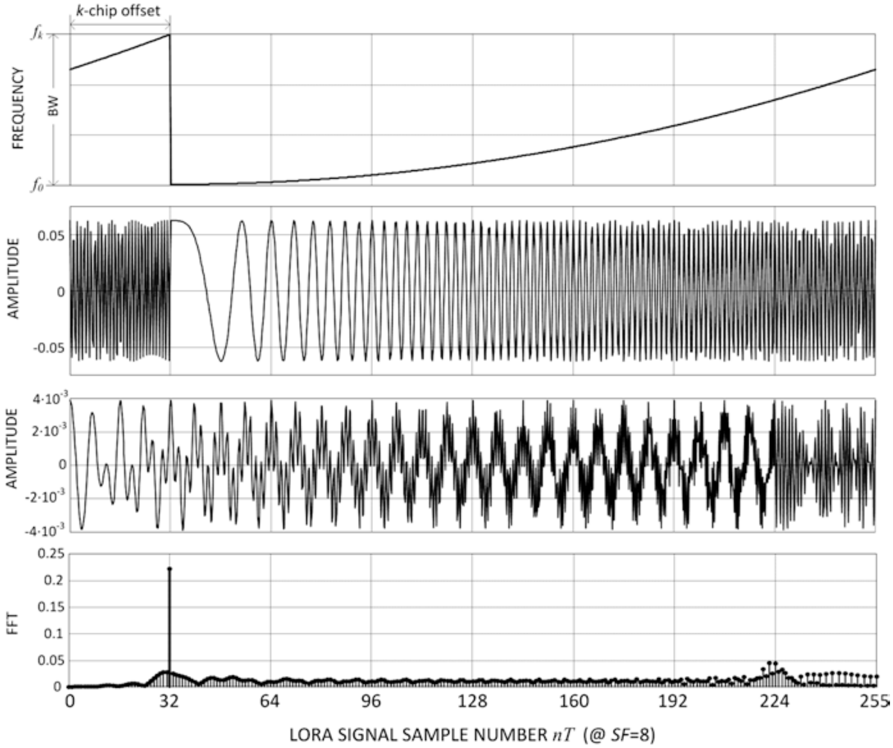


Fig. 5.7 Modulation and demodulation in LoRa: (**a**) frequency offset by k samples (chips); (**b**) a shifted chirp signal; (**c**) a demodulated signal; (**d**) FFT of the demodulated signal

regardless of their offset, presented by the relation (5.4). This feature also makes grounds for the LoRaWAN network planning process in which up to six mutually non-interfering logical networks (each assigned with its own *SF* value) can originate from a single gateway. This concept will be extended in Sect. 5.1.5.3.

$$x_k^{(SF)}(nT) = \sqrt{\frac{1}{2^{SF}}}\exp\left[j2\pi\cdot\frac{\left((n+k)\bmod 2^{SF}\right)^2}{2^{SF+1}}\right] \tag{5.1}$$

$$\sum_{n=0}^{2^{SF}-1} x_m^{(SF)}(nT)\cdot x_k^{*(SF')}(nT) = \begin{cases} 1\ for\ m = k \\ 0\ for\ m \neq k \end{cases} \tag{5.2}$$

$$x_{dem}^{(SF)}(nT) = x_k^{(SF)}(nT)\cdot x_0^{*(SF)}(nT) \tag{5.3}$$

$$\sum_{n=0}^{2^{SF}-1} x_k^{(SF)}(nT)\cdot x_k^{*(SF')}(nT) \approx 0,\ \forall SF \neq SF' \tag{5.4}$$

In order for the described demodulation process to be carried out correctly, the following conditions must be met:

- The transmitted signal phase must be continuous, especially at the transition point. Moreover, the instantaneous phase must be identical at the beginning and at the end of the symbol, which ensures a reliable FFT result. The implementation of this requirement depends on the transmitter.
- The demodulation procedure demonstrated here is possible with ideal time-frequency synchronization, because any precision-related errors in either domain will be interpreted as an additive shift (f_{err}) relative to a correct initial frequency f_k. In the case of traditional CSS binary spatial modulation, this would not be a significant obstacle, because in order to properly distinguish logical zero from unity, one should only determine whether the frequency sweep is increasing or decreasing. In the case of the modified, multistate CSS used in the LoRa system, the information does not modulate the direction of changes in the instantaneous frequency but rather the position of the step change occurrence within the chirp signal duration, expressed by index k. For this reason a preamble consisting of a series of unmodulated chirps is sent prior to the transmission of encoded chirps, in order to achieve synchronization by means of assessing: the beginning of T_s intervals and the absolute initial frequency f_0 (as shown in Fig. 5.8). According to [103, 104], the maximum acceptable uncertainty for achieving correct synchronization is 40 ppm, which, practically, makes it possible to use lower quality, cheaper hardware solutions. After the synchronization, the decoder determines the offset (k) of the encoded symbols in relation to the reference frequency, according to the previously described procedure of multiplication by the coupled signal.

Recapping on the principle of LoRa modulation and demodulation:

- The preamble and 'SyncWord' are used to eliminate time drift and to obtain interval synchronization.
- Modulation symbols are encoded in the form of SF-bit long code words defined in the 2^{SF}-state space, in configurations determined according to the Gray scheme to ensure the greatest possible Hamming distance in order to increase the detective/corrective ability on the receiving side. This capability is controlled by selecting one of the four coding efficiencies $R = \{0.5; 0.57; 0.67; 0.8\}$ defined in the LoRa system by the formula (5.5) as a function of the Coding Rate (CR) taking values from the set $\{1, 2, 3, 4\}$.

$$R = \frac{4}{4 + CR} \tag{5.5}$$

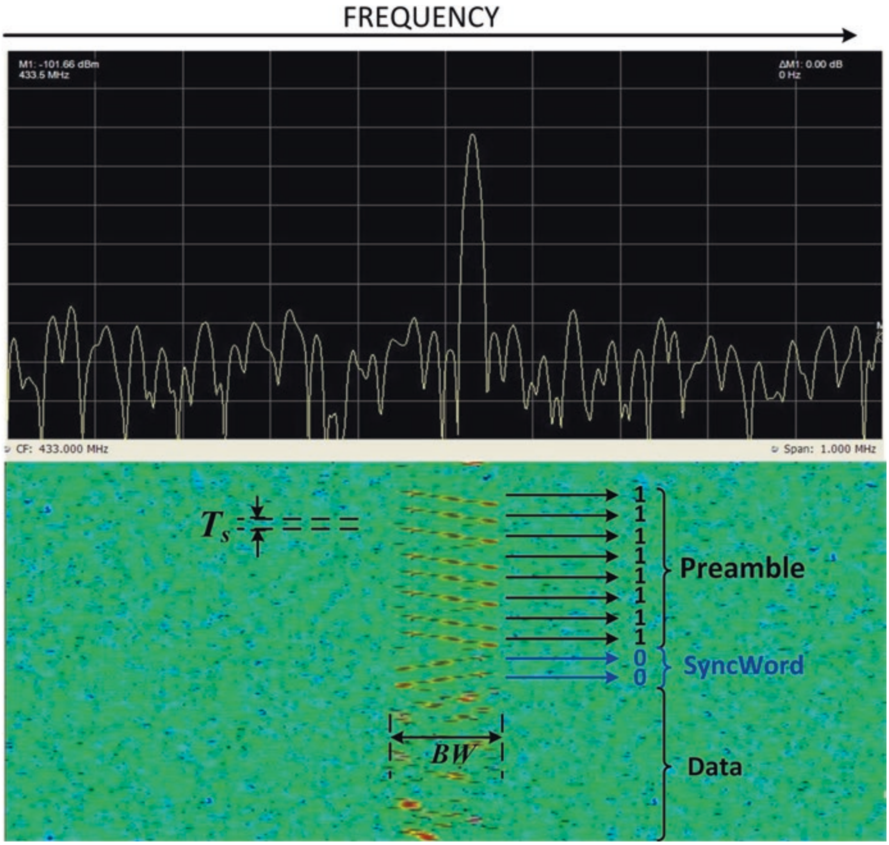


Fig. 5.8 LoRa modulation in time and frequency domains

5.1.5.2 Transmission Rate

If the spreading factor *SF*, the chirp symbol duration T_s and the coding efficiency *R* are known, one can calculate the bit rate R_b, according to the formula (5.6). The calculations, made for various combinations of *BW* and *SF* and for extreme values of *R*, are given in Table 5.3. The dependence determining the duration of the T_s symbol allows to determine the symbol rate R_b, as given in the relationship (5.7) and, on this basis, the resultant chip speed R_c given in formula (5.8). We may conclude that the spread data stream in LoRa is sent at the chip speed R_c [chips/s/Hz or c/s/Hz] equal to the set channel width *BW*. Thus a given bandwidth [Hz] (e.g. 250 kHz) corresponds to the *BW* chip rate [c/s] (e.g. 250 [kc/s]), i.e. in every second of the transmission, there are as many chips sent as there were Hertz transferred in that time.

Table 5.3 Transmission rates (R_b) in LoRa

BW →	***125 kHz***		***250 kHz***		***500 kHz***	
R →	***0.5***	***0.8***	***0.5***	***0.8***	***0.5***	***0.8***
SF ↓	***R_b transmission rate [kb/s]***					
7	3.42	5.47	6.84	10.94	13.67	**21.88**
8	1.95	3.13	3.91	6.25	7.81	12.50
9	1.10	1.76	2.20	3.52	4.39	7.03
10	0.61	0.98	1.22	1.95	2.44	3.91
11	0.34	0.54	0.67	1.07	1.34	2.15
12	**0.18**	0.29	0.37	0.59	0.73	1.17
Total capacity C_{b_kan} [kb/s]	**7.6**	**12.17**	**15.21**	**24.32**	**30.38**	**48.64**

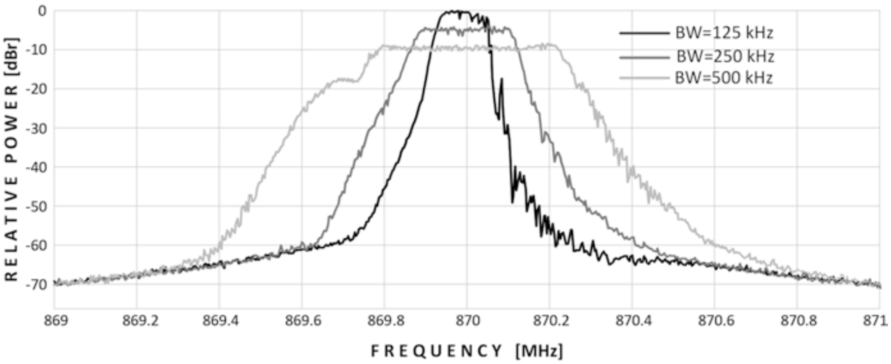


Fig. 5.9 LoRa chirp spectrum measured for different channel width [own source]

Typical bandwidths are 125 kHz, 250 kHz and 500 kHz, with the spectrum shown in Fig. 5.9. The spreading factor is selected from the range of 7–12. Due to the fact that R_c chip rate is unchanged for a given *BW*, as shown by formula (5.7), the T_s symbol/chirp duration (i.e. the time necessary to transmit 2^{SF} chips) is dependent on *SF* and grows with the increasing value of the spreading factor.

$$R_b = SF \cdot \frac{1}{T_s} \cdot R = SF \cdot \frac{BW}{2^{SF}} \cdot \frac{4}{4+CR} [\mathrm{b/s}] \tag{5.6}$$

$$T_s = \frac{2^{SF}}{BW} [s] \Rightarrow R_s = \frac{1}{T_s} = \frac{BW}{2^{SF}} [symbols/s] \tag{5.7}$$

$$R_c = R_s \cdot 2^{SF} [c/s] \Rightarrow R_c = \frac{BW}{2^{SF}} \cdot 2^{SF} = BW [c/s] \tag{5.8}$$

5.1.5.3 Aggregated Capacity, Logical Channels and Packet Transmission Length

As mentioned in Sect. 5.1.5.1, an important feature of multistate LoRa modulation is the total mutual orthogonality of chirp signals with different *SF* values. Due to this feature, individual data streams spread with different *SF* can be considered as six separate *SF7*-*SF*12 logical channels, differing in the bit rate, defined within a single physical *BW*. Thus, the total aggregated transmission capacity C_{b_agr} of a single *BW*-wide channel is the sum of the R_b bit rates obtained for each of the six available logical channels, i.e. according to formula (5.9). The total capacities for various *SF*, *BW* and *R* combinations are given in Table 5.3. The table shows that, with the complete aggregation of logic channels, LoRa modulation facilitates the net transmission capacity equal to 48.64 kb/s, exceeding that for FSK that amounts to 50 kbps physical layer (with no coding overhead included), remembering that the results listed in Table 5.3 already account for the overhead related to the error protection. Of course, individual logical channels can also be used separately and be arbitrarily distributed among end devices, e.g. by allocating separate channels (*SF*) or groups of logical channels at the same time, depending on the transmission needs. However, it is not possible to assign two users with the same *SF* within the same *BW* channel on the same carrier frequency f_c, because after demodulating both signals, they would be indistinguishable. This orthogonality of signals with different *SF* also makes it possible to build up to six networks around a single LoRa base station, each with a different capacity, differing also in range, the analytical justification of which is discussed in Sect. 5.1.5.1.

$$\begin{aligned} C_{b\_agr}\left(BW\right) &= \sum_{x=7}^{12} R_{b\#SFx}\left(BW\right) = \\ &= R_{b\#SF7} + R_{b\#SF8} + R_{b\#SF9} + R_{b\#SF10} + R_{b\#SF11} + R_{b\#SF12}\left[\mathrm{b/s}\right] \end{aligned} \tag{5.9}$$

For example, the total channel capacity with *BW* = 250 kHz and *R* = 0.8 is:

$$C_{b_{agr}}\left(BS = 250\,kHz\right) = 10.94 + 6.25 + 3.52 + 1.95 + 1.07 + 0.59 = 24.43\left[kb/s\right]$$

The selection of the system key parameters, namely, *BW*, *SF* and *R*, should result from the criteria related to the quality of the radio channel; a stronger code protection (expressed in a smaller *R* values) and higher *SF* values should be set for terminals in locations with worse propagation (usually at long distances from the base station) and/or interference conditions. In these more challenging circumstances, it is also recommended to reduce the width *BW* of the channel in order to increase the receiver's sensitivity P_{min}, due to a proportional reduction in the amount of thermal noise, thus increasing the resulting *SNR* value. In more favourable propagation and interference conditions, it is advisable to use smaller *SF* and larger *BW* and *R* values to obtain higher transmission rates, in accordance with the formula (5.6). The quantitative impact of such settings on the Packet Error Rate (*PER*) will be presented in

Sect. 5.2, based on a series of measurements made in a laboratory environment ensuring controlled interference and multipath conditions.

One of the most important criteria to be followed when selecting an appropriate *SF* value is also the duration of the T_p packet at a given bandwidth. Representation of a single bit by means of multiple chips means that these will be transmitted either at higher rates, increasing the bandwidth occupied by the signal (*BW*), or with the same *BW*, increasing the time necessary to transmit the information (T_p). Knowing the duration of a single T_s symbol (chirp), given by the formula (5.7), it is possible to calculate a single packet broadcasting time, containing *M* bytes in the data field ('PHYPayload' in Fig. 5.6). The total transmission time of the packet, therefore, consists of the transmission time of the T_{pre} preamble and *M* bytes of T_M usable data with an overhead. The preamble transmission, for all modem configurations, is given by the formula (5.10), where n_{pre} is the preamble length expressed in the number of symbols (chirps). As shown in [102], the preamble size in the three most popular bands, i.e. EU 863–870 MHz, US 902-928 MHz and EU 433 MHz, equals 8 symbols for LoRa modulation and 5 bytes for GFSK modulation (excluding the US 902-928 MHz band, where GFSK modulation does not apply). The number of symbols forming the data field of the packet and the header (N_{p_h}) and the resulting time of their transmission T_M are defined by the formulas (5.11) and (5.12) [105], respectively. Thus, the total transmission time of the T_p packet can be expressed by the relationship (5.13).

$$T_{pre} = \left(n_{pre} + 4.25\right) \cdot T_s \tag{5.10}$$

$$N_{p\_h} = 8 + \max\left(\frac{8M - 4SF + 28 + 16 - 20H}{4\left(SF - 2DE\right)}\left(4 + CR\right);0\right) \tag{5.11}$$

where

- *M* – number of bytes in the data field in bytes, given in Table 5.1
- *H* – a coefficient equal to '0' when the header is present and '1' when it is missing
- *DE* – a coefficient equal to '1' for the optimization enabled at low transmission rates and '0' without optimization

$$T_M = N_{p\_h} \cdot T_s \tag{5.12}$$

$$T_p = T_{pre} + T_M \tag{5.13}$$

5.1.5.4 Processing Gain, SNR, Sensitivity and MCL

As mentioned in Chap. 4, each of the narrowband IoT systems has a unique technological feature that allows it to obtain either a substantial processing gain G_p (e.g. LoRa, Weightless-P, Ingenu, NB-IoT) or the low noise power (e.g. in SigFox thanks to 100-hertz channels). In LoRa system, the processing gain can be calculated by comparing the following: the transmission rate R_b, calculated according to the formula (5.6) for $CR = 1$ (i.e. for the coding efficiency $R = 0.8$) and BW (125 kHz, 250 kHz, 500 kHz). The formula (22) was used for calculations, assuming rectangular pulses in the time domain for calculating the channel width before spreading BW_{inf} according to the formula (5.14) and possible bandwidths after the data spread (or BW_{SS}). The SNR ratio, on the other hand, can be obtained by referring to the SNR level of 3 dB, appropriate for the simplest two-state modulations, such as BPSK or FSK, according to the relationship (5.15). This ratio will then be used to calculate P_{min} defined by the formula (5.16). The MCL signal dynamics, which is also a measure of the maximum propagation attenuation to be experienced between the LEP end device and the LAP base station, is calculated with Eq. (1), assuming for the LEP devices an effective isotropic radiated power (EIRP) equal to 14 dBm, in accordance with the guidelines for the 'M' band, presented in Table 2.11 for EU863–870 MHz band. Values of individual parameters G_p, SNR, P_{min} and MCL were listed in Tables 5.4, 5.5, 5.6 and 5.7.

Table 5.4 The processing gain G_p [dB] in LoRa system

	The processing gain G_p [dB] $R = 0.8$					
SF →	***7***	***8***	***9***	***10***	***11***	***12***
BW ↓						
125 kHz	11	13	16	18	21	**23**
250 kHz	11	13	16	18	21	**23**
500 kHz	11	13	16	18	21	**23**

Table 5.5 Signal-to-noise SNR ratio [dB] in LoRa system

	Signal-to-noise (SNR) ratio [dB]											
SF →	***7***		***8***		***9***		***10***		***11***		***12***	
R → ***BW ↓***	***0.8***	***0.5***	***0.8***	***0.5***	***0.8***	***0.5***	***0.8***	***0.5***	***0.8***	***0.5***	***0.8***	***0.5***
125 kHz	−8	−10	−10	−12	−13	−15	−15	−17	−18	−20	−20	**−22**
250 kHz	−8	−10	−10	−12	−13	−15	−15	−17	−18	−20	−20	**−22**
500 kHz	−8	−10	−10	−12	−13	−15	−15	−17	−18	−20	−20	**−22**

Table 5.6 Sensitivity P_{min} [dBm] in LoRa system

	Sensitivity P_{min} [dBm]											
SF →	***7***		***8***		***9***		***10***		***11***		***12***	
R → BW ↓	***0.8***	***0.5***	***0.8***	***0.5***	***0.8***	***0.5***	***0.8***	***0.5***	***0.8***	***0.5***	***0.8***	***0.5***
125 kHz	−124	−126	−126	−128	−129	−131	−131	−133	−134	−136	−136	**−138**
250 kHz	−121	−123	−123	−125	−126	−128	−128	−130	−131	−133	−133	−135
500 kHz	−118	−120	−120	−122	−123	−125	−125	−127	−128	−130	−130	−132

Table 5.7 MCL signal dynamics [dB] in LoRa system

	MCL dynamics [dB] (=EIRP$_{=14dBm}$-P$_{min}$)											
SF →	***7***		***8***		***9***		***10***		***11***		***12***	
R → *BW ↓*	***0.8***	***0.5***	***0.8***	***0.5***	***0.8***	***0.5***	***0.8***	***0.5***	***0.8***	***0.5***	***0.8***	***0.5***
125 kHz	138	140	140	142	143	145	145	147	148	150	150	**152**
250 kHz	135	137	137	139	140	142	142	144	145	147	147	149
500 kHz	132	134	134	136	137	139	139	141	142	144	144	146

$$BW_{\inf} = 2 \cdot R_b \tag{5.14}$$

$$SNR = 3dB - G_p \tag{5.15}$$

$$P_{\min} = 10\log\left(k \cdot T \cdot BW\right) + NF_{=7dB} + SNR \tag{5.16}$$

5.2 Weightless (-P): Architecture, Radio Interface and Device Classes

'Weightless (-P)' is an open communication standard dedicated for handling long-range links under conditions of strong propagation attenuation, in the presence of interference, developed and supported by Weightless SIG. The system has been designed for two-way transmission, fully synchronous, for the needs of long-range Internet of Things networks with a limited bandwidth and reduced delay requirements, adapted to work in ISM frequency bands below 1 GHz, as presented in Table 5.8 [106]. Due to the legal restrictions in force in Europe, the main focus (also in Sect. 7.2) will be placed on the 'V band' (863–870 MHz), in particular on 'M' and 'P' sub-bands according to Table 2.11, for which the following restrictions on ERP and duty cycle (*DC*) have been defined:

- Sub-band 'M': 868–868.60 MHz, ERP = 25 mW, $DC \leq 1\%$
- Sub-band 'P': 869.40–869.65 MHz, ERP = 500 mW, $DC \leq 10\%$

This system is – alongside LoRa – one of the leading 'players' in the space of LPWAN systems, as illustrated in Fig. 5.10.

Similar to the LoRa system, the Weightless (-P), recently renamed to 'Weightless', also uses the spread spectrum transmission to improve interference immunity parameters; in this case, however, the spectrum is spread directly (*DS*, see Sect. 4.1.1), using the bit interleaving techniques and data randomization (whitening). The spreading effect, however, is used only in the OQPSK modulation mode. In the second mode, GMSK, there is no spectrum spread (i.e. the dissipation factor $SF = 1$). In the former mode, two *SF* values are available: 4 (Table 5.9) and 8 (Table 5.10).

Table 5.8 Work bands envisaged for the Weightless system (-P) [106]

Band index	Frequency range [MHz]	Band name
I	138.20–138.45	168 MHz
I bis	169.40–169.60	169 MHz
II	314.00–316.00	314 MHz
III	430.00–432.00	430 MHz
III bis	433.05–434.79	433 MHz
III ter	470.00–510.00	470 MHz
IV	779.00–787.00	780 MHz
V	863.00–870.00	868 MHz
V bis	870.00–876.00	873 MHz
VI	902.00–928.00	915 MHz
VI bis	915.90–916.90	915 MHz
VI ter	920.50–929.70	923 MHz

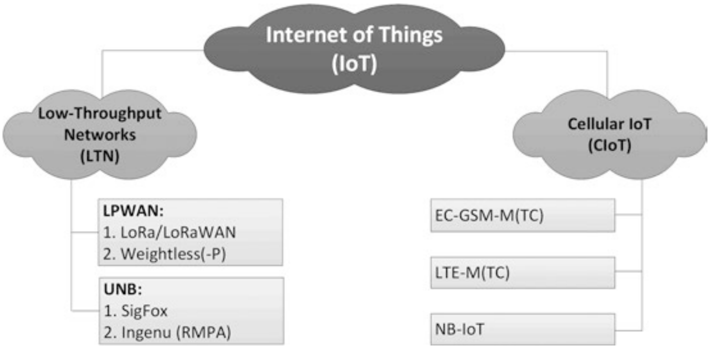


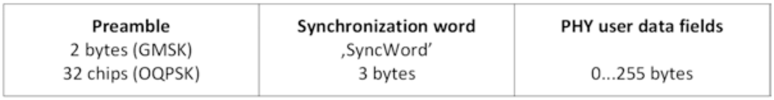
Fig. 5.10 The Internet of Things systems space

Table 5.9 Spectrum spreading sequences in the Weightless(-P) system for (4.1) mode

Input bit.	Chip sequence ($c_0 \ldots c_3$)
0	1010
1	0101

Table 5.10 Spectrum spreading sequences in the Weightless(-P) system for $(8.1)_k$ mode

k index	Input bit.	Chip sequence ($c_0 \ldots c_7$)
0	0	1011 0001
	1	0100 1110
1	0	0110 0011
	1	1001 1100



Preamble 2 bytes (GMSK) 32 chips (OQPSK)	Synchronization word ‚SyncWord' 3 bytes	PHY user data fields 0...255 bytes

Fig. 5.11 packet format in the Weightless(-P) system

For $SF = 8$, two sets of spreading sequences were defined, i.e. $(8,1)_0$ and $(8,1)_1$, used with even and odd bits, respectively. In the synchronization word, however, only $(8.1)_0$ sequence is used.

The Weightless(-P) data packet consists of the following: a preamble and a 24-bit synchronization word, followed by a PHY field containing user data, as shown in Fig. 5.11. In the GMSK modulation mode, the preamble consists of the hexadecimal string 0xAAAA, while in the OQPSK mode, the preamble consists of only zeros (occupying 1 or 2 bytes, respectively, for the spreading factor of 8 and 4). The structure of the synchronization word, in turn, is inconsistent and depends on whether pilot signals and FEC protection coding is used.

In the GMSK mode, the bits are subjected to FSK modulation, where its negative deviation corresponds to the logical '0', while its negative deviation corresponds to positive '1', with the modulation index equal to ½ and the Gaussian smoothing filter with the bandwidth-time product *BT* of 0.3. In OQPSK mode, the chip sequence is first converted into symbols (-1 for $c = 0$ and $+1$ for $c = 1$) and then subjected to modulation through a smoothing filter with raised cosine characteristics and a roll-off factor of 0.8.

Due to the fact that in the IoT applications the uplink traffic (UL) is of major concern, typically containing data generated by sensors, meters, counters, etc., this chapter will be devoted to this link direction. Unlike the downlink (DL), in which all transmissions can be scheduled and synchronized between base stations, the UL requires support for transmissions generated by a large number of mutually non-synchronized end devices (ED). In order to provide larger total capacity, TDMA and FDMA multiple access schemes are utilized in uplink using narrow channels with a width of 12.5 kHz. Working in these channels, on the one hand, means a lower transmission rate but, on the other, the ability to define a larger number of logical channels, which facilitates the increase of multi-access efficiency on the given cell scale. In the UL, the base station can allocate channels either in a 12.5 kHz wide grid or in the form of aggregated eight channels yielding a channel with a total width of 100 kHz. Both channel versions, called narrowband (NB) and wideband (WB) in combination with two possible modulations (OQPSK and GMSK), result in a total of eight operational modes, corresponding to the nominal rates listed in Table 5.11. Their measured spectra, normalized to the peak value of a P_{Tx} transmitter (here equal to 14 dBm), are presented in Fig. 5.12.

The Weightless(-P) system is one of the three solutions of the Weightless SIG consortium, which has been successfully implemented on the market, with a confirmed range of approx. 2 km in favourable LOS conditions in cities.

Table 5.11 Relationships between modulation, transmission rate and channel width in the Weightless(-P) system

Channel width *BW*	Modulation	Encoding efficiency *R*	scattering factor *SF*	Bitrate R_b	Operating Mode[a] OM_x
12.5 kHz (narrowband mode, NB)	OQPSK	0.5	8	0.625 kb/s	$\boldsymbol{OM_1}$
		0.5	4	1.25 kb/s	$\boldsymbol{OM_2}$
	GMSK	0.5	1	5 kb/s	$\boldsymbol{OM_3}$
		1	1	10 kb/s	$\boldsymbol{OM_4}$
100 kHz (wideband mode, WB)	OQPSK	0.5	8	6.25 kb/s	$\boldsymbol{OM_5}$
		0.5	4	12.5 kb/s	$\boldsymbol{OM_6}$
	GMSK	0.5	1	50 kb/s	$\boldsymbol{OM_7}$
		1	1	100 kb/s	$\boldsymbol{OM_8}$

[a] According to the OM definition in **Chapter 6.2**

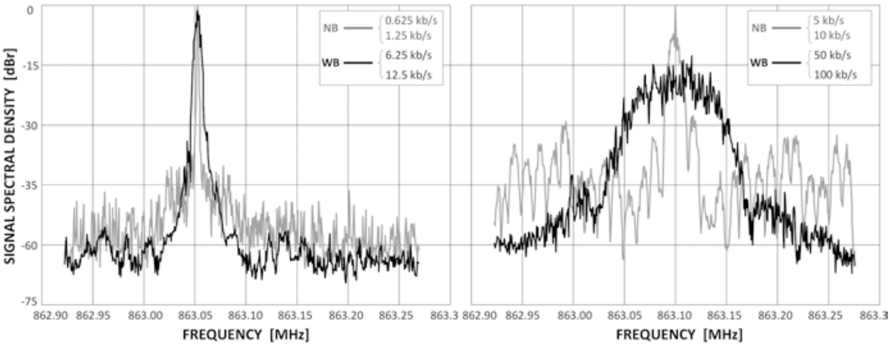


Fig. 5.12 Weightless(-P) system signal spectra measured for modes: (left) NB (12.5 kHz); (right) WB (100 kHz)

The Weightless-N standard (officially approved in 2015) assumed operation in ultra-narrowband mode in the frequency band below 1 GHz, using DBPSK modulation, but only in the UL direction. This restriction did not meet the approval of the user community interested in using the IoT systems, as described in more detail in Sect. 2.3.2. As a result, the system was eventually recalled, despite successful range tests carried out in 2015 in London. Its target range was to be 5 km in urban conditions [87].

The Weightless-W standard (officially approved in 2013) was designed to work within the 470–790 MHz digital dividend in the so-called white TV spaces. The use of different modulations was envisaged, from DBPSK to 16-QAM. The rate adaptation was arrived at via spectrum spreading at several *SF* levels (up to 1024). The disproportion in the link energy budget, resulting from EIRP being about 20 dB higher in the base station relative to UE's EIRP, was compensated by using 64 times narrower frequency channels for UL traffic compared to DL traffic, leading to the reduction in the noise level in the channel by approx. 18 dB. The target range was to be 5 km and 10 km for urban conditions, respectively, for indoor and outdoor conditions [87].

5.3 SigFox: Architecture, Radio Interface and Device Classes

The SigFox system is one of the main representatives of the class of ultra-narrowband systems (UNB, described in Sect. 4.3), where the service coverage has the peak priority, leaving out the transmission rate as a matter of lower importance. It is a product of a consortium bearing the same name [107], authorizing specific entities (companies) to which it provides base station modules and permits to use the systems as operators. End users, who are interested in using SigFox in their own networks (e.g. sensor, counter, etc. networks), become clients to these entities [108]. These users, on their part, have access to a limited market offer on client stations, i.e. from programmable modules to systems adapted for cooperation with other microprocessor platforms, e.g. Arduino, Raspberry Pi (Fig. 5.13a). The only base station systems available so far for individual users, intended for development purposes, is the SDR Dongle chip (Fig. 5.13b) with factory-limited sensitivity of −65 dBm. It allows the user to verify their own design in terms of compliance with the SigFox protocol and to test transmission efficiency, effectiveness (measured by the Packet Error Rate) and the sufficiency of embedded confirmation mechanisms, etc. It also gives the opportunity to test the system in the context of end devices interaction with the base station, similar to real ones, although within a range usually limited to a few to a dozen of meters or so. As shown in Fig. 5.14 (blue, live coverage; purple, countries under roll-out), the area of Europe has already been largely covered by the operating range of SigFox operator networks, which is by far due to long ranges obtained from a single base station.

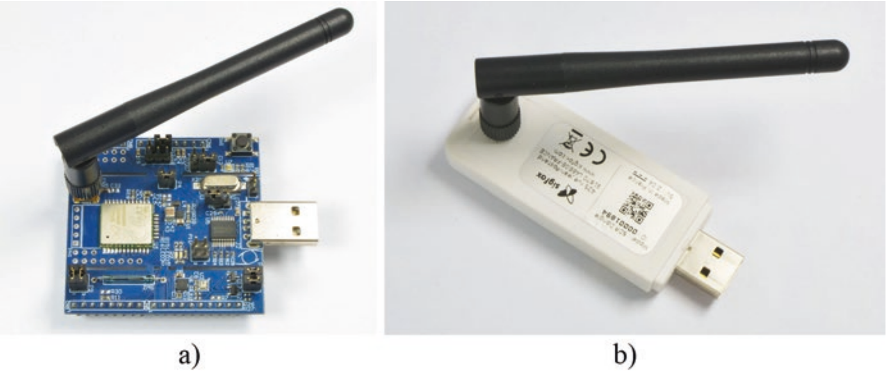

a)
b)

Fig. 5.13 SigFox exemplary devices: hardware implementations: (**a**) a client station (Digi-Key); (**b**) a limited-sensitivity developer base station (Digi-Key)

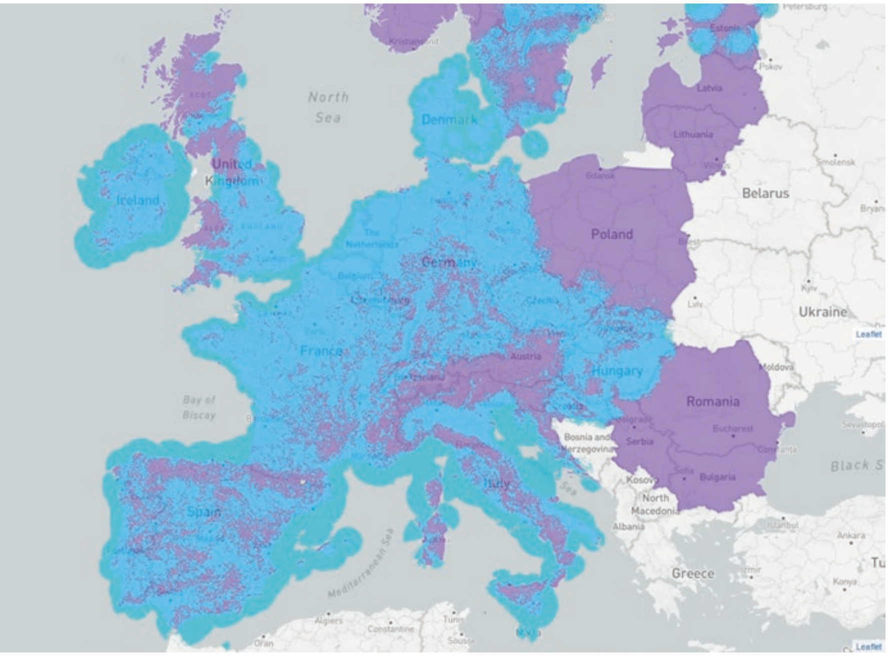


Fig. 5.14 Coverage of Europe by networks operating in the SigFox standard. Status as of 2020 [available at www.sigfox.com]

Significant energy efficiency is required from SigFox system devices, like from any other UNB system (e.g. Ingenu, Weightless-N), which is strongly emphasized in the RFTDMA multiple access protocol (described in detail in Sect. 4.3.3), in which the transmission channel is randomly selected for time and frequency without initiating any competitive mechanisms. The closest equivalent of RFTDMA is the ALOHA protocol with no pre-listening for channel occupancy. However, unlike the classic ALOHA, carrier frequencies in UNB systems are selected from a continuous range (here, with a total width of 192 kHz, as described below) instead of a predefined discrete set of channels. This feature allows for the use of weaker quality transmitters in the terminals, whose uncertainty of the generated frequency is greater than the channel bandwidth *BW* alone (which is only 100 Hz in the UL link). This feature provides another advantage of such systems, namely, reduced costs of transmitting and receiving devices, although negatively affecting the values of the *NF* (noise factor) and the *IM* (implementation margin), to the detriment of the link budget. Each data packet is repeated on the UL three times, each time on a different, random channel, whereby the transmission of each individual message takes 6.24 s. This, in turn, results in processing gain G_p resulting from these repetitions equal to approximately 4.8 dB. The measured time-spectral structure of the transmission in the SigFox system for the UL is presented in Fig. 5.15, where *PSD* stands for the

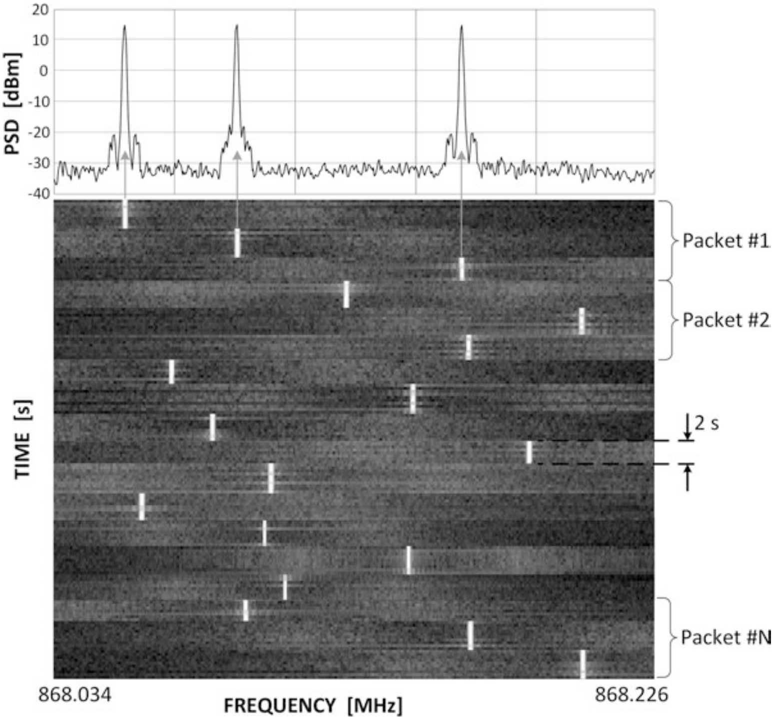


Fig. 5.15 Time-spectral structure of transmission in SigFox UL

power spectral density. It can be seen here how a single packet is carried on three consecutive frames scattered randomly in the available spectrum.

The most important features of the SigFox system are [108]:

- Operation in a fragment of the ‘M’ sub-band (according to Table 2.11), covering a total width of 192 kHz in the range between 868.034 MHz and 868.226 MHz.
- Nonsymmetrical two-way transmission (UL/DL).
- Bandwidth in UL transmission: 100 Hz.
- Bandwidth in DL transmission: 600 Hz.
- Network topology: star.
- The maximum permitted EIRP is 14 dBm (25 mW).
- Applied modulations: DBPSK (in the UL link), GFSK (in the DL link).
- R_b transmission rate in the UL link: 100 b/s.
- R_b transmission rate in the DL link: 600 b/s.
- P_{min} sensitivity, at $NF = 5$ dB in the DL or 3 dB in the UL, $SNR = 7$ dB and G_p processing gain of 4.8 dB, is approx. –144 dBm in the UL and –134 dBm in the DL.
- Attenuation dynamics $MCL = 158$ dB in the UL and 161 dB in the DL.

- Total length of the transmission frame: 26 B (including 12 B user data packet, payload). Detailed frame structure in the UL/DL links is presented in Sect. 4.3.
- UL frame transmission time: 2.08 s.
- Number of transmissions of a single packet: 3.
- System limitation of the maximum number of messages sent: 140 packets/day. It results from the necessity of meeting the condition $DC = 1\%$. This constraint means that, given the transmission time necessary to transmit a single message (repeated three times) of c.a. 6 s, the total transmission duration in an hour is limited to 36 s, a time just sufficient to emit statistically almost six messages. On a daily scale, this translates to a maximum of about 140 messages (packets).
- Operational range (coverage): up to 50 km in open areas, up to 5 km in built-up areas.