5 An introduction to Sigfox radio system

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5.1 Internet of things, a new usage for the radiocommunication industry

The radiocommunication era started in 1895 with the first Marconi's experiments. Hundred years later, radiocommunication evolution is largely driven by cellular systems and their billions of subscribers. Cellular systems started with analog, and then went to digital. In the late 1990s, digital 2G systems have been used for machine-to-machine (M2M) communication. M2M takes advantage of existing data bearers, primarily designed to address human-to-human (H2H) or human-to-machine (H2M) usage. They are not optimized for the emerging usage of Internet of things (IoT). Many definitions exist for IoT [1] with a quite strong focus on network. Here we give an object-centric definition for the IoT, which is "the ability, for objects, to connect the Internet without being considered, near or far, as computer."

This definition implies that communication is only a side feature of a connected object. Implementation of IoT communication must be easy and cost-effective, particularly if there is no electrical power natively in the object to be connected. Compared to H2H, H2M, and M2M, IoT is a new usage, with new constraints for radiocommunication technologies:

- Low cost: In an object, communication function must have only a marginal cost, compared to the total cost of the object, as it is an additional function only. At time of printing, volume price for Sigfox modules is as low as 2$. Target price is estimated to be as low as 0.2$, with mass production.
- Low volume of data: Connected objects transmit information such as sensed data, status, index, and alarms and receive commands or parameters. Compared to machines that may be complex and may require M2M communication, connected objects have a single function, which communicate infrequent small application packets [2].
- Massive number of connected objects: Thanks to low-cost and easy-to-use IoT communication function, it becomes possible to connect many types of objects, resulting in much higher density of connections per square kilometer that is usually seen in cellular systems. In urban area, density of connected objects may be over 50k per square kilometer [2].

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5.2 Low-power wide-area network: a new paradigm in radio network engineering

Low-power wide-area network (LPWAN) acronym was forged by Machina Research in June 2013 [3] to refer to emerging communication systems. Whereas IoT is about usage, LPWAN is about radio technology. LPWAN novelty resides in mixing two contradictory notions: low power and wide-area network. LPWANs have a series of key characteristics, as follows:

- Massively asymmetrical: LPWAN base stations are in small numbers to reduce infrastructure cost. Therefore, each base station may serve tens of thousands of connected objects.
- Connected objects transmitting at low power: Use of radio transmitter, with tens of milliwatt of transmit power, is essential to get low complexity in communication modules and to reduce the cost of the connection function. Low transmit power means also small batteries and, sometimes, even no battery thanks to energy harvesting techniques.
- High sensitivity in base stations: As a consequence of low power in connected objects, high sensitivity in base stations is a must to get wide-area connectivity with one-hop communication. Multihop connection is not the preferred option to get wide-area coverage, because of energy spent in signaling.
- Complexity moved from objects to base stations: Low power in connected objects means that protocol complexity must be kept minimal in objects also. In LPWAN, complexity balance between objects and network is opposite to the trend of the past decade in telco system, where telephone sets become more and more complex, going from electromechanical objects to analog electronics, then to digital, and now with sophisticated signal processing.
- No strong latency requirement: LPWANs address IoT usage where application is neither time-critical, nor real-time; several seconds for uplink or downlink latency are affordable in most of IoT use cases.
- No high-speed mobility requirement: LPWAN technologies address application that are stationary or at walking/cycling speed (e.g., up to 30 km/h).

These system characteristics are new technical constraints for radio design engineers. Therefore, they require new techniques to be solved. Ultra-narrow band (UNB) is a disruptive answer, based on revisited technology developed before World War II.

5.3 Ultra-narrowband: a disruptive way to use radio spectrum

5.3.1 Tuning: an old answer to capacity challenge

Since the beginning of radiocommunication, engineers have put a lot of effort in receiver tuning. Tuning is about adjusting a receiver so that its center frequency is aligned with one of the transmitters you want to listen to. Its objective is to have several radio transmissions occurring at the same time in the same place and without interfering each other.

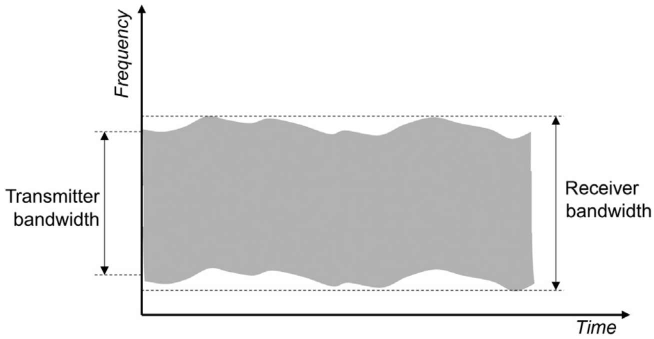

FIGURE 5–1 Conventional narrowband system.

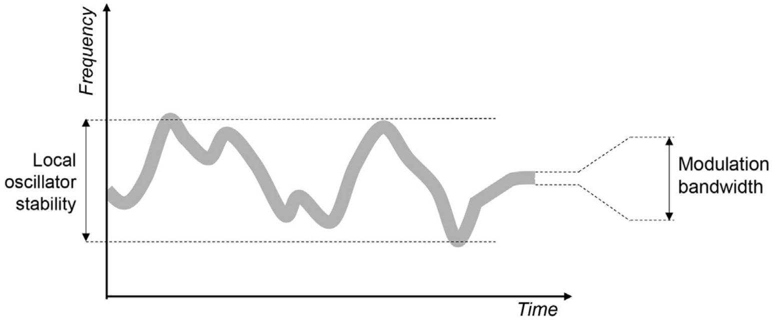

FIGURE 5–2 UNB modulation bandwidth.

In the past, tuning was about adjusting an inductance or a capacitor to match frequencies of local oscillators in transmitter and receiver. In practice, this process has to be permanent, because local oscillator of transmitter and receiver is not perfect and may drift quite significantly over transmission duration. When relative drift of transmitter (Tx) and receiver (Rx) oscillators is lower than the transmitter bandwidth (see Fig. 5–1), most part of signal energy resides within receiver bandwidth. Tuning is manageable with known techniques such as low drift oscillators or adaptive frequency control in receivers.

5.3.2 The 1-ppm limit

Paradoxically, receiver tuning becomes much more difficult with progress in microelectronics. Availability of integrated fractional-N phase-locked loops (PLLs), which may have a frequency synthesis step as low as 1 Hz, makes possible modulation rates of a few tens of symbols per second even with carrier center frequency up to a few gigahertz. In such case, local oscillator fluctuation of the PLL is clearly larger than the modulation bandwidth (see Fig. 5–2). Definition of UNB captures this paradox: UNB is a radiocommunication system that exhibits a modulation bandwidth lower than oscillator stability.

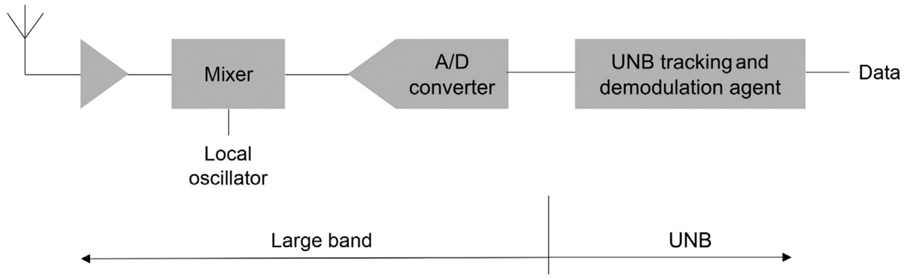

FIGURE 5–3 SDR for UNB reception.

When applied to subgigahertz technologies, UNB may be defined as a modulation bandwidth smaller than 1 ppm of carrier center frequency.

In UNB communication systems, receiver tuning issue reaches a new level of complexity. Its answer cannot be in conventional receiver architecture: the answer is a software-defined radio (SDR) receiver. SDR listens for a large spectrum range with a high dynamic range and a software agent searches for the signal of interest and continuously tracks its carrier center frequency, as a human radio operator would do (see Fig. 5–3).

5.3.3 Ultra-narrowband benefits for low-power wide-area networks

As such, having an SDR receiver is nothing new, but using SDR to overcome local oscillator unstability of transmitter is, from our best knowledge, a new approach in radiocommunication systems. When used along with UNB modulation scheme, it brings new opportunities and/or benefits as detailed in the following subsections.

5.3.3.1 Frequency channel allocation revisited

UNB modulation in transmitter and SDR receiver enlarge drastically the frequency space for sharing medium access. In conventional narrowband systems, operating frequency band is split into a couple of communication channels, each of them having an occupied bandwidth from tens to hundreds of kilohertz. In subgigahertz spectrum, UNB brings thousands of pseudo-channels. As an example, the 25 mW unlicensed frequency band in Europe [4], ranging from 868.0 to 868.6 MHz, brings 6000 pseudo-channels of 100 Hz width. This large amount is a real game changer: instead of implementing mechanism to share a scarce frequency resource from central point, objects may select randomly carrier center frequency, without excessive collision rate. Even if hundreds of objects transmit at the same time, reception in base station is made possible with corresponding number of demodulation agents (see Fig. 5–4).

5.3.3.2 Capacity given by base station processing power

UNB modulation and SDR receiver in base station give new opportunity for capacity increase, especially when base stations have a large coverage. Ref. [5] shows theoretical

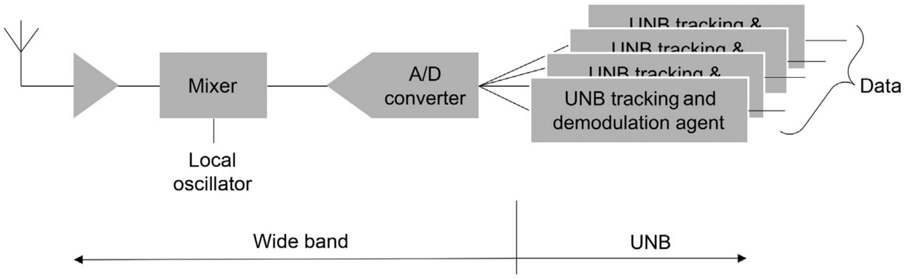

FIGURE 5–4 SDR implementation for UNB capacity.

time/frequency duality of narrowband communication when used in random unslotted time-frequency ALOHA networks. But, when using unlicensed spectrum, where regulation limits maximum power in transmission, UNB benefits from unlimited time to expand transmission. Furthermore, base station capacity leverages high dynamic range in SDR receivers because it is possible to receive messages from objects close to a base station along with messages far from base station. When looking for increased capacity, Ref. [6] shows the benefit of successive interference cancellation.

5.3.3.3 Complexity pushed back into core network

As explained in Sections 5.3.3.1 and 5.3.3.2, use of UNB removes a lot of complexity in objects. They do not need to care about channel selection and fine frequency tuning, because everything is managed by base stations and in the core network, where almost unlimited processing power is available. This balance of complexity is quite new in the telecommunication where more processing power in terminals supports the quest for more throughput and more multimedia capabilities in cell phones.

5.3.3.4 Ultra-narrowband robustness in unlicensed spectrum

In essence, LPWAN may be deployed in licensed or unlicensed spectrum. In practice, LPWANs go for the later because they have no license fees. Unlicensed spectrum, known as short range device (SRD) in Europe and instrumental, scientific and medical (ISM) in the United States, may be shared by a number of different systems, as long as they comply with technical constraints for sharing the spectrum. As these constraints are always minimalist, many different systems and technologies may coexist in SRD/ISM bands. As a consequence, spectrum occupancy in unlicensed bands is unpredictable: it is up to each system/technology to cope with interferences.

UNB brings robustness to LPWANs in unlicensed spectrum where many systems may coexist. Its high injection factor focuses Tx energy in a small spectrum interval allowing good signal-to-noise ratio. High dynamic SDR receivers leverage this in base stations.

5.4 Triple diversity ultra-narrowband, the Sigfox communication rules

5.4.1 Protocol versus communication rules

Triple diversity UNB (3D-UNB) is the name of communication rules for radio interface of the Sigfox solution (see Fig. 5–5). 3D stands for triple diversity, that is, diversity in time, frequency, and space. Table 5–1 gives 3D-UNB key numerical figures. A fully featured description of Sigfox communication rules is publicly available on the Internet [7]. The following subsections address key characteristics of 3D-UNB and give rationale for their design choices.

Thanks to UNB, Sigfox designed a very simple radio interface with low level of complexity in objects. The clue is randomness in managing time, frequency, and space. Randomness allows absence of coordination between transmitter and receiver. This is the reason why Sigfox radio interface is more a set of communication rules than a full communication protocol.

5.4.2 Uplink communication rules

5.4.2.1 Six steps to build an uplink radio burst

As any other communication systems, construction of a 3D-UNB uplink radio burst requires several steps from applicative level to physical level (see Fig. 5–6).

5.4.2.2 Small payload size for Internet of things usage

In communication protocols, payload size is a hint on the need of fragmentation for carrying large application messages. Multimedia applications benefit from variable payload sizes (ranging up to 1500 bytes, and even more with jumbo frames) that are available in IP-based

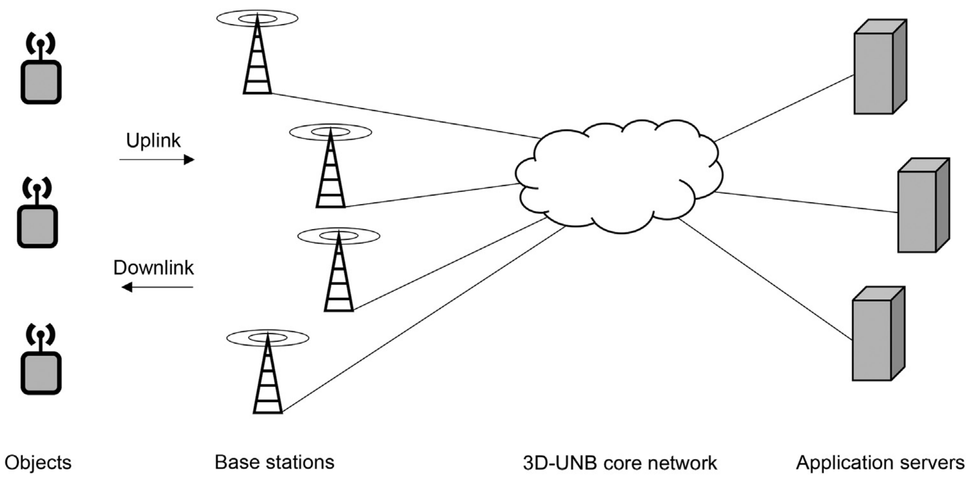

FIGURE 5–5 Overall architecture of Sigfox solution.

Table 5–1 3D-UNB characteristics in uplink and downlink.

Characteristics	Uplink (UL)	Downlink (DL)
Payload size	0 bit to 12 bytes	8 bytes (fixed length)
Total MAC/LINK overhead	8–10 bytes	2 bytes
Total PHY overhead	6 bytes	18 bytes
Modulation rate	100 baud or 600 baud	600 baud
Modulation scheme	Differential binary phase shift keying	Gaussian frequency shift keying
Transmit power	25 mW in Europe 150 mW in United States[a]	500 mW[b]
Frequency band	Subgigahertz unlicensed bands	

[a]Other values may exist in other countries, since maximum transmit power is defined by national regulations.
[b]Total transmit power may be balanced between multiple downlink messages, transmitted at the same time.

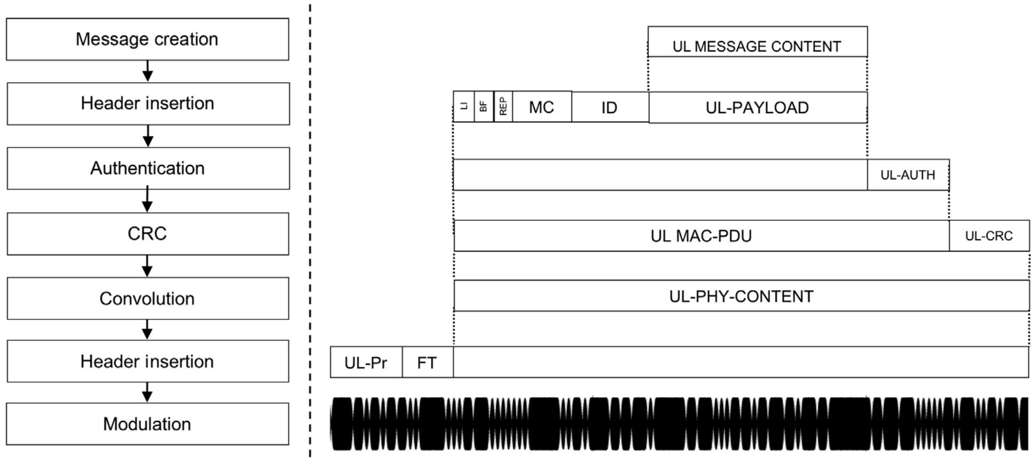

FIGURE 5–6 Uplink communication stack.

networks. IoT usage has different constraints for LPWAN systems. Instead of being able to carry largely variable size messages, IoT constraints is more about small application packets with limited overhead for the sake of energy saving.

Payload of 3D-UNB application messages goes from 0 to 12 bytes. This is enough to carry environmental data as well as a GPS position. Twelve bytes of application data are transmitted in a radio burst of only 2.08 seconds at 100 baud (see Table 5–3), with 1.8 mJ of energy per useful application bit, when using most recent radio modules rated at 25 mW/3.3 V in 25 mW transmission mode.

5.4.2.3 Replay attack protection with rolling counter

MAC/LINK header contains a message counter (MC) that is incremented after each message transmission. It is used in authentication algorithm as a rolling counter for replay attack protection. 3D-UNB core network rejects all messages received outside a sliding acceptance window. Replaying an old message is always possible but lag to do it must be greater than roll-over time, which is given by formula:

$$Roll\_over\_time = \frac{2^{MC\_length}}{Message\_rate}$$

With an MC length of 12 bits and a message rate of 140 messages per day in Europe, because of regulations, roll-over time of MC counter is 29 days. This value is large enough to get a reasonable replay attack protection for data collected by IoT sensors.

5.4.2.4 Convolution code for local or remote combining

For each uplink message, an object may transmit one or three uplink frame(s) (see Fig. 5–7). Transmitting one frame results in the lowest object power consumption, whereas transmitting three frames for the same message provides increased resiliency. Moreover, multiple transmissions give an opportunity to have combining algorithms in base station (local combining) or in 3D-UNB core network (remote combining). Local combining benefits from frequency diversity and convolution codes, whereas remote combining adds spatial diversity to combining processing.

To get efficient combining algorithms, each frame in a message is encoded with a different polynomial, as defined in Table 5–2.

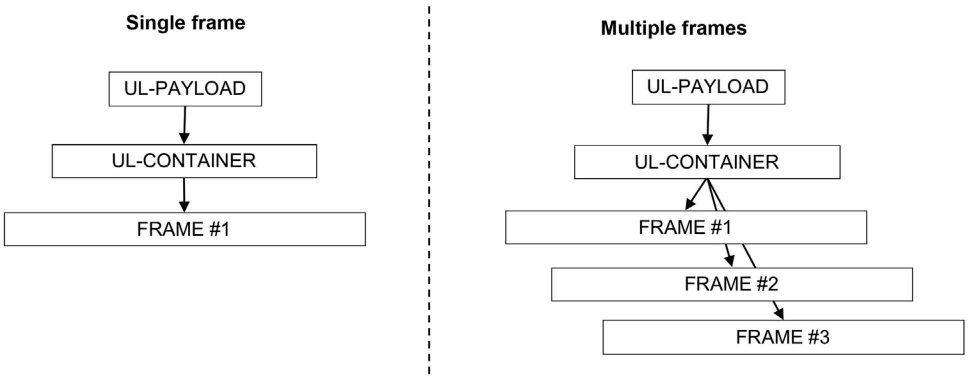

FIGURE 5–7 Principle of single or multiple transmission.

Table 5–2 Polynomials for convolution coding of uplink frames.

Frame emission rank	Polynomial
First	$R = 1$ (identify)
Second	$R + 1 + X + X^2$
Third	$R = 1 + X^2$

Table 5–3 Uplink frame type values.

Message type	UL Payload	LI value (binary)	UL-AUTH field size (bytes)	MAC-PDU size (bytes)	Frame length (bytes)
Application message	empty	00	2	8	14
	1 bit (=0)	10	2		
	1 bit (=1)	11	2		
	1 byte	00	2	9	15
	2 bytes	10	4	12	18
	3 bytes	01	3		
	4 bytes	00	2		
	5 bytes	11	5	16	22
	6 bytes	10	4		
	7 bytes	01	3		
	8 bytes	00	2		
	9 bytes	11	5	20	26
	10 bytes	10	4		
	11 bytes	01	3		
	12 bytes	00	2		
Control message	5 bytes	11	5	16	22
	6 bytes	10	4		
	7 bytes	01	3		
	8 bytes	00	2		

Frame rank	FT value (binary)	FT value (hexa)
First	0b0000001101011	0x006B
Second	0b0011011100000	0x06E0
Third	0b0000000110100	0x0034
First	0b0000010001101	0x008D
Second	0b0000011010010	0x00D2
Third	0b0001100000010	0x0302
First	0b0001101011111	0x035F
Second	0b0010110011000	0x0598
Third	0b0010110100011	0x05A3
First	0b0011000010001	0x0611
Second	0b0011010111111	0x06BF
Third	0b0011100101100	0x072C
First	0b0100101001100	0x094C
Second	0b0100101110001	0x0971
Third	0b0100110010111	0x0997
First	0b0111101100111	0x0F67
Second	0b0111111001001	0x0FC9
Third	0b1000110111110	0x11BE

Radio burst duration (@100baud)	Radio burst duration (@600baud)
1.12 s	187 ms
1.20 s	200 ms
1.44 s	240 ms
1.76 s	293 ms
2.08 s	347 ms
1.76 s	293 ms

5.4.2.5 Frame type, a multipurpose field

Frame type is an important field of MAC/LINK header. It is 13 bit long and carries two pieces of meta-information (see Table 5–3).

The first meta-information is the length of uplink MAC-PDU (see Fig. 5–6). Uplink MAC-PDU size is five discrete values only, depending on payload size (see Table 5–3).

The second meta-information is the frame rank, when multiple frames transmitted for an uplink message (see Section 5.4.2.4).

As frame type field is critical for decoding remaining parts of a frame, it is coded in 13 bits, and with a Hamming distance of at least five for all frame type values (see Table 5–4).

5.4.3 Downlink communication rules

5.4.3.1 Six steps to build a downlink radio burst

Construction of a 3D-UNB uplink radio burst requires six steps from applicative level to physical level (see Fig. 5–8). Full description is available in [7] and key characteristics of downlink 3D-UNB transmission are given in Table 5–1.

Fig. 5–8 depicts construction steps for downlink communication from applicative level to PHY level (i.e., from base station perspective). The key characteristics of 3D-UNB downlink communication rules are presented in the following subsections from object perspective, that is, from PHY level up to applicative level.

Table 5–4 Hamming distance of frame type values.

	0b1000110111110	0b0111111001001	0b0111101100111	0b0100110010111	0b0100101110001	0b0100101001100	0b0011100101100	0b0011010111111	0b0011000010001	0b0010110100011	0b0010110011000	0b0001101011111	0b0001100000010	0b0000011010010	0b0000010001101	0b0000000110100	0b0011011100000	0b0000001101011
0b0000001101011	7	7	6	8	5	6	7	6	7	5	8	5	6	5	5	6	6	**0**
0b0011011100000	9	5	6	10	7	8	5	6	5	5	6	9	6	5	7	6	**0**	6
0b0000000110100	5	11	8	6	5	6	5	6	5	7	6	7	6	5	5	**0**	6	6
0b0000010001101	6	6	9	5	8	5	6	5	6	6	5	6	7	6	**0**	5	7	5
0b0000011010010	6	8	9	5	6	7	10	7	6	6	5	6	5	**0**	6	5	5	5
0b0001100000010	7	7	6	6	7	6	5	8	5	5	6	5	**0**	5	7	6	6	6
0b0001101011111	6	6	5	5	6	5	6	5	6	8	7	**0**	5	6	6	7	9	5
0b0010110011000	5	5	10	6	7	6	5	6	5	5	**0**	7	6	5	5	6	6	8
0b0010110100011	6	6	5	5	6	9	6	5	6	**0**	5	8	5	6	6	7	5	5
0b0011000010001	10	6	7	7	6	9	6	5	**0**	6	5	6	5	6	6	5	5	7
0b0011010111111	5	7	6	6	9	10	5	**0**	5	5	6	5	8	7	5	6	6	6
0b0011100101100	6	6	5	9	8	5	**0**	5	6	6	5	6	5	10	6	5	5	7
0b0100101001100	7	5	6	6	5	**0**	5	10	9	9	6	5	6	7	5	6	8	6
0b0100101110001	8	6	5	5	**0**	5	8	9	6	6	7	6	7	6	8	5	7	5
0b0100110010111	5	7	6	**0**	5	6	9	6	7	5	6	5	6	5	5	6	10	8
0b0111101100111	9	5	**0**	6	5	6	5	6	7	5	10	5	6	9	9	8	6	6
0b0111111001001	10	**0**	5	7	6	5	6	7	6	6	5	6	7	8	6	11	5	7
0b1000110111110	**0**	10	9	5	8	7	6	5	10	6	5	6	7	6	6	5	9	7

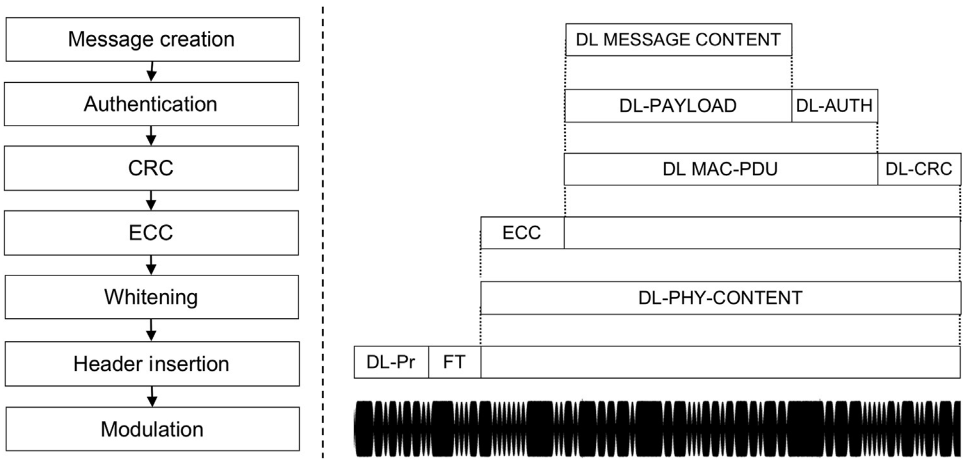

FIGURE 5–8 Construction steps of downlink radio bursts.

5.4.3.2 Object-triggered downlink communication

Ability to have downlink communication at random is a request coming from H2H services, (i.e., incoming calls). In the case of fixed landline telephone, this feature requires almost no energy because the line current is only a few micro amps, when headset is on hook. In the case of cellular phones, this feature drains milliamps, because of permanent cell reselection and location update mechanisms. Having such a drain current is not acceptable in IoT objects for two reasons:

- It would require power source of significant size, which is not compatible with IoT concept where radio connection is just a side feature in the object
- In many cases, IoT usage requires always uplink communication, but downlink is either of seldom use or with no strong latency constraint.

For 3D-UNB systems, every downlink message is triggered by a previous uplink message, sent by object. Hence, it is up to an object to decide, on a per-message basis, whether to pull for a downlink message or not. This feature implements a bidirectional flag (BF) in uplink MAC/LINK header (see Fig. 5–6) for triggering downlink communication (see Fig. 5–9).

5.4.3.3 Relationship between uplink and downlink carrier center frequency

Section 5.3.3.1 introduces concepts and benefits of random selection of uplink carrier frequency for UNB communication and how inaccuracy of local oscillators is managed by SDR processing in base station. An equivalent issue exists for receiver tuning in downlink. Once again, work-around comes from base stations that use SDR also for downlink communication.

This is done by defining a fixed frequency gap between carrier center frequency of an uplink message and carrier center frequency of the onward downlink message

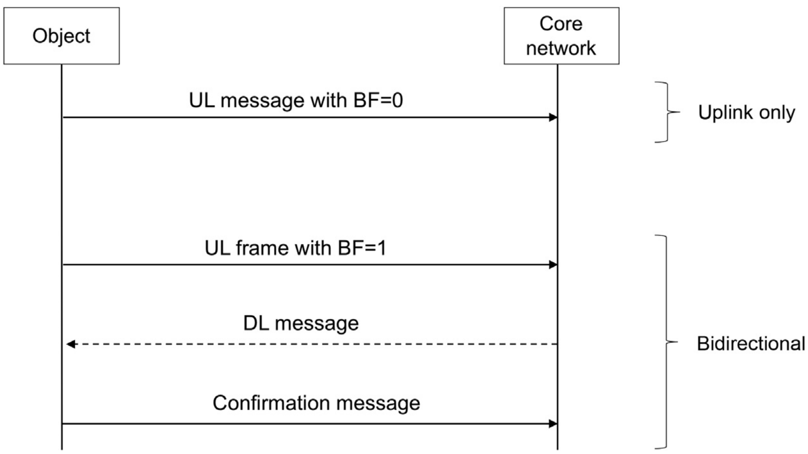

FIGURE 5–9 Uplink or uplink and downlink communications.

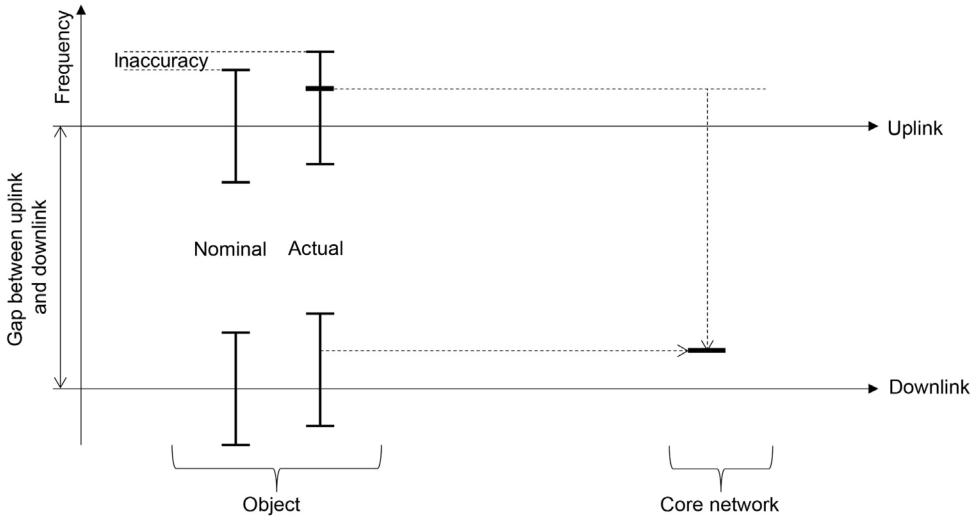

FIGURE 5–10 Compensation of object frequency inaccuracy in core network.

(see Fig. 5—10). Local oscillator inaccuracy is transparently compensated by core network, as long as it remains constant between uplink transmission interval and downlink reception interval. This short-term stability is easy to achieve even in low-cost/low-complexity radio hardware of IoT objects.

5.4.3.4 Downlink authentication reusing uplink context

Authentication of downlink incoming messages uses corresponding uplink context in three different ways.

The first authentication check is implicit: an object opens a time and frequency window where it expects a downlink message. Other downlink messages, which base station may transmit out of this window, will be ignored by object.

The second authentication check uses whitening function that core network applies to have evenly distributed symbol transitions in downlink radio bursts. Whitening function uses pseudorandom generator whose initialization value includes object identifier (ID) and MC value coming from corresponding uplink message. If de-whitening output contains too much errors, it is rejected.

The third authentication is more classic and based on AES128 cryptographic function. Downlink messages contain an authentication field (DL-AUTH in Fig. 5—8) that is evaluated with parameters derived from uplink context (see Fig. 5—11). This is possible because each downlink message is triggered by uplink message (see Section 5.4.3.2). Object ID and MC values are derived from corresponding uplink message; authentication key is known by core network and object.

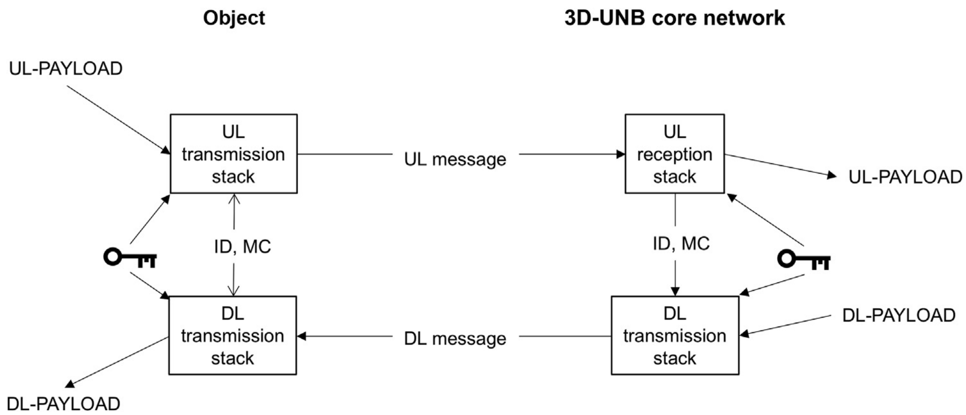

FIGURE 5–11 DL-AUTH field evaluated with uplink context.

5.5 Seven questions on Sigfox radio interface

5.5.1 Why Sigfox radio access network is not a cellular network?

Since their very early beginnings, cellular systems have been based on the concept of frequency reuse. Frequency reuse is very efficient to get capacity over very large coverage with a small set of frequencies, but it implies complex attachment procedures to detect and connect the network. Power consumption in cellular phones is significantly impacted by these procedures, particularly when moving.

On the contrary, in order to keep 3D-UNB as simple as possible, all 3D-UNB base stations listen for the same frequency band. There is no procedure in objects to retrieve the proper frequency to be used in a given area and no extra power consumption when objects are mobile. 3D-UNB objects just have to know the international telecommunication union (ITU) zone, where they are deployed and use the frequency intervals selected by 3D-UNB network. A 3D-UNB system is like built with a single worldwide cell.

5.5.2 Why is there no attachment procedure in Sigfox radio access network?

Attachment procedures were designed to be able to receive an incoming call at once, wherever mobile phones are in the network. In many IoT use cases, there is no need for downlink messages triggered only by core network. That is why there is no attachment procedure in 3D-UNB systems. Only implicit attachment is available: each time an object transmits an uplink message, the network can detect where the object is. If a downlink message is requested, core network is able to select adequate base station for downlink transmission. Benefit of implicit attachment is less power consumption and less complexity in objects.

5.5.3 What is cooperative reception?

Cooperative reception is a side benefit of noncellular nature of 3D-UNB system. As all base stations are on the same frequency, large overlap of base stations coverage exists. Whereas overlaps are kept to the minimum in cellular systems, they are beneficial to 3D-UNB systems because they bring spatial diversity. Several base stations may receive an uplink radio burst simultaneously. Multiple received packets are then de-duplicated in core network, before transmission to application server. Cooperative reception improves quality of service without extra complexity in objects; everything is done in core network.

5.5.4 Why is there no destination address in Sigfox radio bursts?

In local area networks, it is common to have source and destination address fields in each packet. This is because several nodes may share a common medium of communication. In 3D-UNB systems, there is no object-to-object communication: all messages go from objects to application servers or from application servers down to objects (see Fig. 5–12).

In uplink, destination of radio bursts is unambiguous: it is all base stations that are in the vicinity of a transmitting object. So, no destination address is needed, resulting in smaller radio bursts. In core network, messages are routed to application servers, thanks to a database that links object identifiers to application servers.

In downlink, radio frames do not have any address fields at all, because downlink transmission is triggered by an uplink message (see Fig. 5–10). Carrier center frequency and time interval for downlink transmission are defined by corresponding uplink message (see

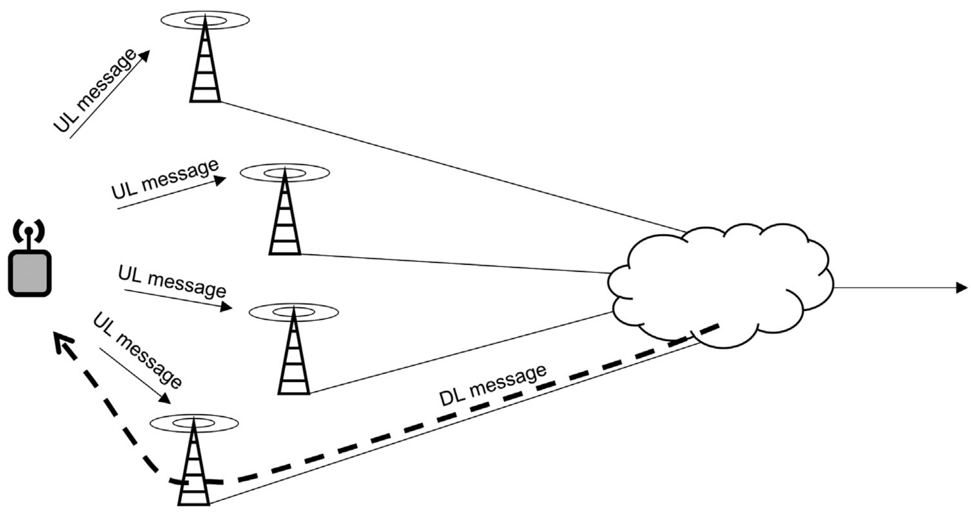

FIGURE 5–12 DL base station selection with cognitive algorithm.

Fig. 5–11), creating a kind of implicit address. Possible collision in downlink frequency/time slot is resolved by whitening function and authentication that use ID and MC values (see Section 5.4.3.4). So, no explicit address field is needed in downlink frames.

5.5.5 Why does Sigfox radio access technology use ALOHA for accessing the spectrum?

ALOHA [8] implements a minimalist medium-sharing technique: pure random access. The benefit is in its lightweight implementation. The drawback is its poor capability to withstand medium or high offered load. Success rate is good only when offered load is kept low or very low.

3D-UNB communication rules use ALOHA to access the spectrum for the following two reasons:

- It is easy to implement in low-cost/low-complexity objects and fully compliant with spectrum-sharing techniques of SRD/ISM unlicensed frequency bands.
- It is efficient thanks to UNB that gives extra capacity to the unlicensed frequency bands that are limited. In other words, it is as if ALOHA over UNB becomes a two-dimensional ALOHA: uplink messages are evenly distributed over time and frequency with a de facto reduction of offered load per frequency pseudo-channel.

5.5.6 Why is Sigfox radio access technology cognitive?

Cognition in telecommunications means that a system changes its parameters according to its environment or usage it sees. 3D-UNB systems are cognitive in two ways.

Base stations implement cognitive process in their SDR signal processing by allocating demodulating and decoding agents for each radio signal of interest in received spectrum. The more signals are received in parallel, the more demodulating and decoding agents run in parallel in a base station.

Core network implement cognitive algorithm to select base station for downlink transmission. Because of large coverage overlaps, several base stations are in communication range of an object. When a downlink communication is triggered by an uplink message, all surrounding base stations are a candidate for downlink transmission. Core network run cognitive algorithm to select the best base station for each downlink message (see Fig. 5–12). Various parameters may be included when selecting base station for downlink transmission such as load, interference level, frequency balancing, and available transmit power.

5.5.7 Why do Sigfox objects control the network and not the other way around?

Coordination of terminal nodes by a central base station is common in licensed radio systems, such as cellular or private mobile radio networks, because it helps to get most of the frequency bands, paid by operators. The drawback of this approach is additional signaling messages and/or reception time in terminal nodes to acquire and keep synchronization with base stations.

IoT objects are drastically constrained in power consumption, so the less energy is consumed in network coordination, the better it is for objects. The simplest implementation is to have transmit frequency and time selected by objects, that is, without any prior synchronization with surrounding base stations. Avoiding such synchronization procedures is beneficial for power consumption in objects, as long as collision rate is kept reasonably low. This is possible thanks to UNB, which gives increased capacity (see Section 5.3.3), and 3D-UNB communication rules, which implement pure random access (see Section 5.5.5).

3D-UNB base station behavior depends on what they receive from surrounding objects. Base stations have to be ready to receive uplink radio packets, at any time and on any frequency selected by objects. This is why the network is controlled by objects.

5.6 Conclusion

This chapter presents Sigfox radio system, which is optimized for small infrequent messages of IoT connectivity. Its radio interface implements UNB over the air, SDR processing in base stations, and cognition in core network. UNB and SDR processing are beneficial for capacity and simplicity even when operated in unpredictable spectrum, because they bring robustness to interferers, selectivity, and sensitivity. Cognition brings spatial diversity in uplink and load optimization in downlink. In the future, it is expected that SDR will allow improved uplink reception capabilities (e.g., with successive interference cancellation) and improved downlink capacity thanks to optimization algorithms for base station selection. These improvements will add no complexity to objects, that will remain simple and low energy, which is critical for the IoT.

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