An introduction to Sigfox and LoRa PHY and MAC layers

Guillaume Ferré, Eric Pierre Simon

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Guillaume Ferré and Eric Pierre Simon
IMS Laboratory - University of Bordeaux - Bordeaux INP
351 cours de la libération 33400 Talence (FRANCE)
guillaume.ferre@ims-bordeaux.fr

In this paper we present an introduction to Sigfox and LoRa physical and MAC Layers.

I. Sigfox modulation

A. Sigfox Physical layer

Sigfox is based on ultra-narrow band (UNB) physical layer where the binary data are broadcast with a differential binary phase shift keying (DBPSK) modulation at a very low rate $R_{b,s} = 100\ bps$. Thus, the transmitted signal occupies a band of approximatively $W_s = 100Hz$. Sigfox nodes use a Random Frequency and Time Division Multiple Access (RFTDMA) to transmit their signals. The frequency hopping is done inside a bandwidth $B >> W_s$. This ensures channel diversity and deep fading protection. The expression for the signal (or packet) transmitted by the Sigfox node n_s is:

$$r_s^{n_s}(t) = \sum_{k \in \mathcal{S}_s} A_k g(t - kT_s) e^{j2\pi f_p t} \quad (1)$$

where

- $T_s = \frac{1}{R_{b,s}}$ is the symbol period,
- A_k is the DBPSK symbol transmitted at time kT_s,
- $f_p \in \pm\{\frac{B}{2}\}$ the baseband frequency used to transmit the packet of several bytes,
- $\mathcal{S}_s$ is the set of the symbols transmitted during the packet,
- $g(t)$ is the pulse shaping filter of bandwidth W_s.

B. Sigfox Mac layer

Sigfox Mac layer relies on RFTDMA. It allows active nodes to access randomly in time and frequency to the wireless medium without any contention-based protocol. It can be referred to the ALOHA-based protocol, however the carrier frequencies are chosen in B inside a continuous interval, instead of a predefined discrete set. Indeed, at the receiver side, the demodulator listen on the totality of the bandwidth B without recognizing *a priori* the carrier frequency used by the emitting device. Therefore, identifying the emitted message can be obtained only after decoding all received signals in B. The random access seems to be efficient in protecting the device from interferences and seems to be likewise of interest since it limits the device's energy consumption. Nevertheless, the uncontrolled medium access leads to introduce interferences between active nodes. This will be explained in the following sections.

According to a feature of Sigfox protocol (linked to the duty cycle of the considered ISM band), an active node could transmit about 140 packets per day containing 12 bytes of payload. In addition, each message can be sent up to 3 times on different frequencies with the aim of improving reliability. The packet structure is given as follows [1]:

- a preamble (4 bytes),
- a frame synchronization part of 2 bytes,
- a device identifier of 4 bytes,
- a payload of up to 12 bytes,
- a Hash code to authenticate the packet in Sigfox network (variable length),
- a Cyclic Redundancy Check (CRC) syndromes of 2 bytes for security and error detection.

The $\mathcal{S}_s$ size is based on these 6 previous parameters. The bi-directional communication is performed only when it is asked by the transmitter. In this case, it can mention that it is on listening mode until it receives data. In real propagation condition Sigfox spans 50 to $100km$ of distances and ensures to manage about 1 million devices per base station [2]. This claims is true whereas Sigfox does not share B with an other IoT technology. Indeed, as it is demonstrated in the next sections, the Sigfox capacity to manage a million of devices will vanish with the coexistence of a LoRa network.

II. LoRa modulation

The following sections are dedicated to introduce the LoRa physical layer based on the patent [3] and an example of MAC layer [4]. For more details the reader is referred to [5].

A. LoRa physical layer

LoRa is based on Chirp Spread Spectrum (CSS) modulation. CSS was proposed for the first time for communication systems by Winkler [6] and application to digital communication by Berni [7]. CSS is considered as a subcategory of Direct-Sequence Spread Spectrum (DSSS). CSS is compliant with IoT network needs because it makes it possible to overcome the receiver's sensitivity issue and increase the communication range at the cost of a reduced spectral efficiency. The spectrum spreading in LoRa is achieved using a chirp signal that can be described by its instantaneous phase $\phi(t)$ or a specific time function $f_c(t)$. $f_c(t)$ is called the raw chirp that:

- increases linearly, for an up raw chirp, from an initial value $-\frac{B_l}{2}$ to a final value $\frac{B_l}{2}$,
- decreases linearly, for a down raw chirp, from an initial value $\frac{B_l}{2}$ to a final value $-\frac{B_l}{2}$,

where B_l stands for the ISM signal bandwidth used for the communication[1]. The raw chirp time duration is equal to the symbol period T_l. $f_c(t)$ is defined as follows:

$$f_c(t) = \pm\frac{B_l}{T_l}t \tag{2}$$

The relationship between the bandwidth and the symbol period is given by the following equation:

$$T_l = \frac{2^{SF}}{B_l}$$

where SF stands for the spreading factor exponent $SF \in [7, ..., 12]$. Let D_l be the symbol rate of the transmitted signal and $D_{b,l}$ the bit rate, then:

$$D_l = \frac{D_{b,l}}{SF}$$

Longer range is achieved by varying the spreading factor and thus the symbol duration as B_l remains the same $\forall SF$. In addition, to meet highly robust communication it is possible to vary a coding rate[2].

With LoRa, symbols are obtained from a binary combination of SF bits. Each symbol is associated to a unique chirp. The different chirps are orthogonal to each other in order to retrieve the symbols at the receiver without inter-symbol interference. If we note M the set of symbols, the chrip associated to the symbol m, $m \in [0, M-1]$, is obtained by delaying the raw chirp $f_c(t)$ by $\tau_m = \frac{m}{B_l}$. The (symbol→chirp) association process is described in figure 1 (a), (b) and (c).

[1] B_l depends on the used ISM band and can be chosen equal to 125, 250 or 500 kHz

[2] As the LoRa physical layer is un-published, we have no official information from Semtech concerning the used channel coding algorithm. However it seems to be an hamming (8,4) code.

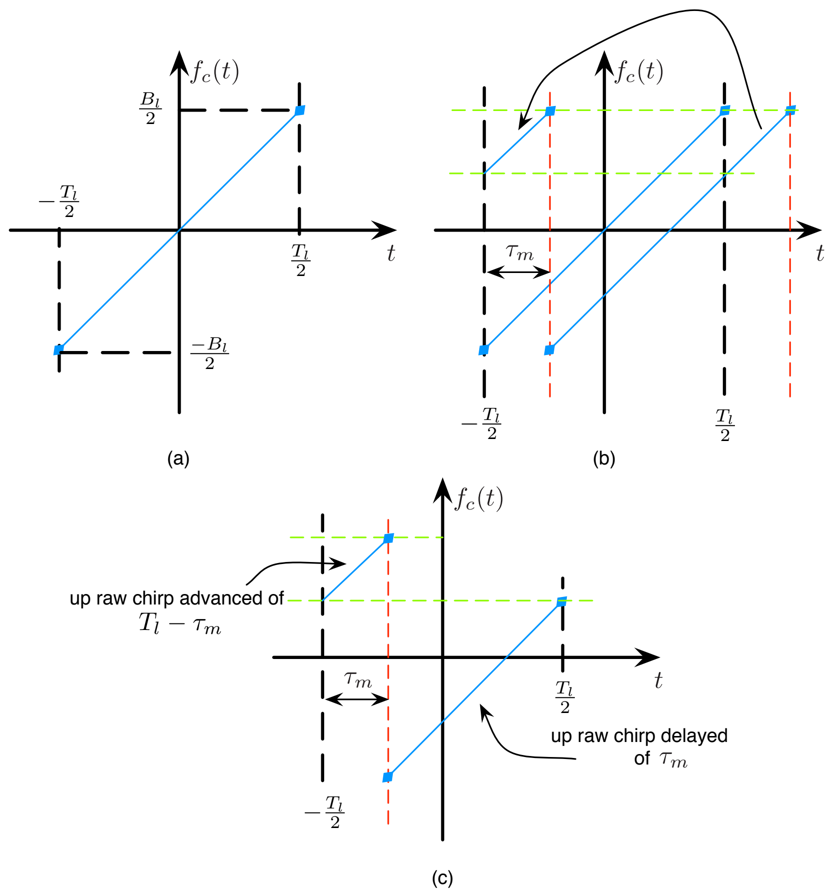

Figure 1: (symbol→chirp) association process - (a) up raw chirp - (b) process illustration - (c) chirp associated to the mth symbol

The chirp outside $[-\frac{T_l}{2}, \frac{T_l}{2}]$ is cyclically shifted in the interval $[-\frac{T_l}{2}, -\frac{T_l}{2} + \tau_m]$ as shown in figure 1 (b). Thus, the chirp associated to the transmission of the m^{th} symbol is decomposed of 2 parts:

1) from $t \in [-\frac{T_l}{2}, -\frac{T_l}{2} + \tau_m[$, raw chirp (up ou down) advanced of $(T_l - \tau_m)$,
2) from $t \in [-\frac{T_l}{2} + \tau_m, \frac{T_l}{2}]$, raw chirp (up ou down) delayed of τ_m.

For an up chirp, we obtain:

$$f_c^m(t) = \frac{B_l}{T_l}(t - \tau_m) + B \qquad \text{for } t \in [-\frac{T_l}{2}, -\frac{T_l}{2} + \frac{m}{B}[$$
$$f_c^m(t) = \frac{B}{T_l}(t - \tau_m) \qquad \text{for } t \in [-\frac{T_l}{2} + \frac{m}{B}, \frac{T_l}{2}]$$

Thus, the expression of the baseband transmitted signal by the node n_l is given as follows:

$$r_l^{n_l}(t) = \sum_{k\in\mathcal{S}_l} e^{j2\pi f_{c,k}(t-kT_l)(t-kT_l)+j\phi_0} \quad (3)$$

where $f_{c,k}(t)$ represents the transmitted chirp at time kT_l, $\mathcal{S}_l$ the set of transmitted symbols inside the packet p and ϕ_0 an initial phase. The chirps $f_{c,k}(t) \in \{f_c^i(t)\}$ $i \in \{0,\dots,M-1\}$ are mutually independent and uniformly distributed.

If we note K the $\mathcal{S}_l$ size, thus the silent time duration of the LoRa node will be at least equal to $\frac{KT_l}{d_c} - KT_l$. Thus, from $t + KT_l$ to $t + \frac{KT_l}{d_c}$ the node will be silent.

B. LoRaWAN: a LoRa Mac layer

LoRaWAN is an open standard developed by the LoRa Alliance. It's one of the possible MAC layer for the LoRa modulation and obviously the well known. The LoRaWAN specification defines 3 categories of nodes:

- Class A: a basic class of LoRa that is implemented in all LoRa chips. It allows bi-directional communications which is usually originally started by the node in an asynchronous way. The uplink transmission triggers two short downlink receive windows. The transmission slot is scheduled when needed by the node in a random time basis. According to LoRaWAN specifications, class A is an ALOHA based-protocol. It is obviously interesting to know that this class is the most suitable for metering nodes.
- Class B: this class is conceived to guarantee uplink and downlink separation. Nodes are synchronized using a beacon transmitted by the gateway. Thus, they can receive information from Internet without sending requests. This optional class is particularly suitable for conceiving remote controlled objects at any time.
- Class C: the node has continuously open receive windows that are closed only while transmitting. Compared to A and B classes, C class consumes more energy to operate but it offers the lowest latency.

The format of an uplink message is as follows [8]:

$$Preamble - PHDR - PHDRCRC - Payload - CRC$$

Where :

- $PHDR$: Physical Header,

- $PHDRCRC$: Physical Header CRC.

Following the uplink communication step, the node open two different receive windows. Once the expected message is received on the first window, the second window would not be opened. LoRa operates in the ISM bands, in Europe, it uses 868 MHz as band and 868.1, 868.3 and 868.5 MHz as sub-bands (433MHz is also available). According to the regulatory authorities, some specifications should be respected while transmitting to acquire immunity against interferences. As it is indicated in LoRaWAN specifications, the ETSI regulations [9] allows either the use of a duty-cycle or a transmission management protocol called LBT (Listen Before Talk Adaptive Frequency Agility). To comply with this condition, LoRa uses a duty-cycle of 0.1 to 1 $\%$, notably, for available data rates of 0.3kbits/s to 50kbits/s.

The time on air depends on severals parameters, such SF, B, the size of the payload, the coding rate, etc. For more details on the LoRa MAC structure see [4].

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