On Chirp Signaling & Demodulation

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Every modulation technique has a niche it operates best. When it comes to low power transceivers that are intended to operate over a range of channel variations, chirp signal models are becoming preferable. Communication devices/sniffers that continuously sense their vicinity & SDR that are expected to operate over a vast RF range for experimentation, are also becoming equipped with physical radio layers based on chirping. This is in addition to the wave-shaping advantage chirp signal has for the operation of echolocation systems, like radar. Chirp in tandem with spectrum spreading yields a modulation scheme with its on special characteristics, in which the scheme is called Chirp Spread Spectrum (CSS). The what, why and how to take advantage of CSS followed by its demodulation mechanisms are addressed here.

1 Chirp signal

1.1 The what

Chirp signal is the one whose frequency varies over time. This variation can be from low to high frequency (up-chirp) or from high to low frequency (low-chirp). For instance, the signal on Figure 1 is an up-chirp.

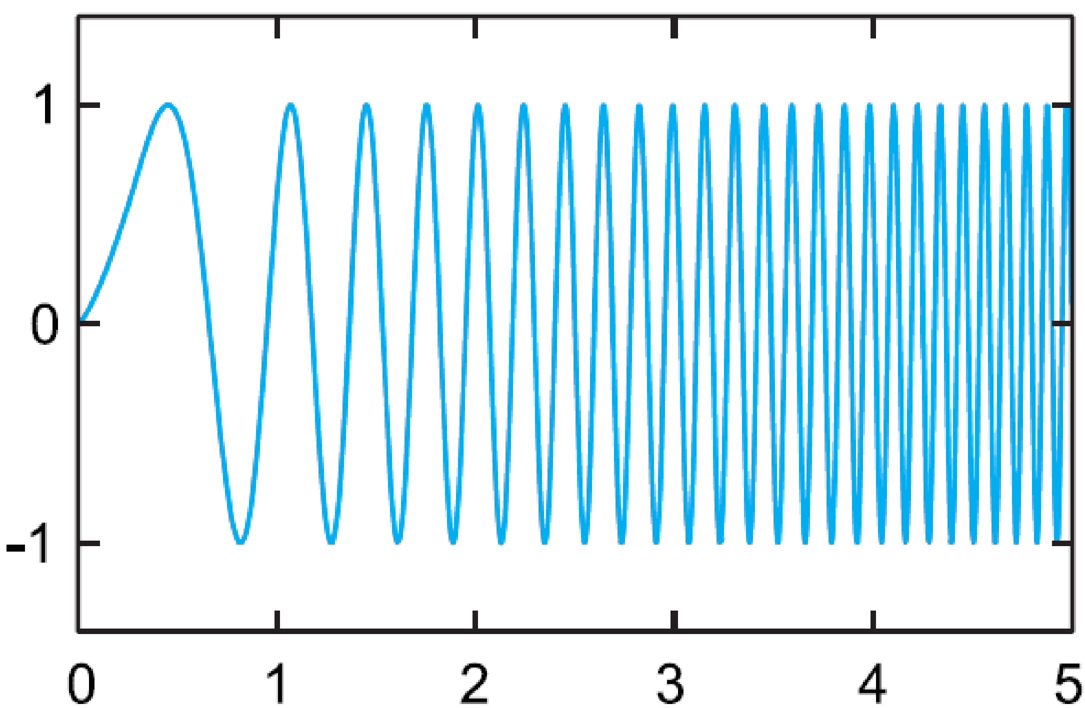

Figure 1: A simple up-chirp

To phrase it in terms of the commonly known signal, chirp is a ***frequency modulated sinusoidal signal***. This also enables mathematically expressing chirp with the parameters we are already familiar with. The equation $x(t) = Acos(\theta(t))$, where $\theta(t)$ is the phase and A is the amplitude, could model the basic chip signal. In the general complex plane, this can be stated as:

$$x(t) = Ae^{j\theta(t)} \tag{1}$$

Hence, the ***instantaneous frequency*** of chirp signal at time t becomes:

$$f(t) = \frac{1}{2\pi}\frac{d\theta(t)}{dt} \tag{2}$$

For a sinusoidal with constant frequency f_o , the phase is simple linear expression $\theta(t) = 2\pi f_o t + \phi = \omega_o t + \phi_o$. But for a chirp signal, the phase would have quadratic or any other form. When the phase takes a quadratic form such that

$$\theta(t) = 2\pi\alpha t^2 + 2\pi f_o t + \phi \tag{3}$$

As already stated, the derivative of this phase form gives the instantaneous frequency which changes linearly for this form and hence the signal is called **linear-frequency chirp**.

$$f(t) = 2\alpha t + f_o = kt + f_o \tag{4}$$

The derivative of $f(t)$ (or second derivative of $\phi(t)$) which in this case is $k = 2\alpha$ represents the rate of change of the *instantaneous frequency*, and it is usually called ***chirpyness*** of the signal. The chirpyness can be found as the slope as the chirp's initial frequency f_o changes its When $\alpha > 0$, the waveform is an up-chirp and when $\alpha < 0$, we have a down-chirp.

1.1.1 Generating chirp

Analog chirp signals can be generated with voltage controlled oscillators which are commonly used in frequency modulation (FM) systems. It can also be generated with digital filters (implemented for example with Python/MATLAB/C++ or similar convenient high level language) and then can be converted into analog form with DAC (Digital to Analog Converter) followed by reconstruction LPF (Low Pass Filters).

Python's scipy DSP library does have a builtin function to generate a simple chirp signal, as depicted in the code listing below.

```python
import numpy as np

def chirp_generator():
    # Import the numerics/chirp/plotting packages
    import numpy as np
    import matplotlib.pyplot as plt
    from scipy.signal import chirp

    #define sampling and time range
    fs = 100 #sampling frequency in Hz
    t =np.arange(start = 0, stop = 1,step = 1/fs)
    #total time base from 0 to 1 second
    x = chirp(t, f0=1, t1=0.5, f1=20, phi=0, method='linear')
    plt.plot(t,x);
    plt.show()
```

Listing 1: Simple chirp generating & plotting function

1.2 The Why

From the angle of this project, one motive for integrating *chirp signaling based modulation* into the radio interface layer of the system could be its potential for real-time sensing and localization of communication nodes. As applied and shown in the proprietary radio technology called LoRa [4], there are also other features why CSS (Chirp Spread Spectrum) could be preferable for some specific use cases of digital wireless communication. Chirp signaling combined with spectrum spreading has shown to be better than the classical digital signaling schemes like FSK with respect to some parameters and applications.

The CSS technology proved to be the top modulation method for low-power and long-distance communication, hence mainly in the IoT arena. And again from this project perspective, the locally connected nodes should be energy efficient if they are to continuously sense and audit their environment, and also if they are battery operated. Moreover, the gateway is expected to make a long range communication connecting the node to the outside world (the wide area network, the cellular network or other).
Generally, the merits that come with CSS are:

- long range connectivity with a very low power
- fading resistant
- increased receiver sensitivity
- Doppler shift resistant (high tolerance to frequency misalignment between receiver and transmitter which is common in mobile communications)

These merits are the result of both the processing gain of the spread spectrum technique and the intrinsic nature of chip signal modeling that generalizes sinusoidal signals.
Due to the processing gain associated with LoRa, the output power of the transmitter can be reduced compared to a conventional FSK link still maintaining the same or better link budget. Since it can operate at a very low power and so difficult for detection, it has a potential of being used for military like purposes.

1.3 CSS Modulation (The How)

A simple digital modulation scheme can be constructed by mapping binary input data into up-chirp and down-chirp, just like FSK modulation. But as noted previously, spectrum spreading based chirp signaling provides more positive features, and it is the how of CSS modulation presented here.

Just as in most digital communication systems, each symbol is modulated at baseband stage of the system. For CSS modulation, this can be named *chirping*. The high level the transmitter side as commonly used by LoRa wireless technology is shown in Figure 2. In this or other sort of CSS modulator, each CSS signal represents SF (Spectrum Factor) amount of bits that is found after spreading the original binary.

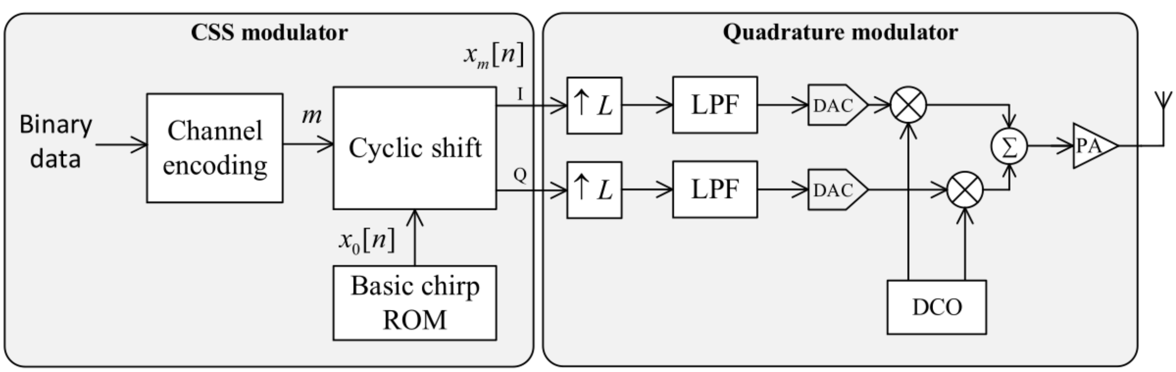

Figure 2: Transmitter side with CSS Modulation [3]

A brief outline of the transmitter side looks the following.

1. the **channel encoder** converts binary data into a stream of SF-bit M symbols, where

$$M = 2^{SF} \tag{5}$$

   - the larger SF, the higher the processing gain which makes detection (demodulation) easier. Clearly there will be a cost, which is lower transmission rate

2. **symbol mapper** converts the group of M symbols into CSS symbol. It does this by cyclically shifting a basic chirp by an amount equivalent to the symbol index m at the end to provide the digital baseband CSS symbol

    - Given each CSS symbol consumes BW amount of bandwidth (or from $-BW/2$ to $BW/2$ centering the chirp at $0Hz$), the **chirp rate** (or the 'chirpyness') becomes

    $$k = \frac{BW}{T_{sym}} = \frac{BW^2}{M} \tag{6}$$

    measured in $Hz/second$. Here T_{sym} is the time CSS symbol takes as the chirp *sweeps* from the minimum $(-BW/2)$ to the maximum frequency $(BW/2)$

3. the **mixer** (or *quadrature modulator*) converts the baseband into passband signal by multiplying it with the carrier frequency from the DCO (Digitally Controlled Oscillator). But before this process, each baseband CSS symbol is up-sampled & converted into analog form

2 Demodulation

At the receiver, after getting done with RF processing stage, demodulating CSS signal mainly involves *de-chirping* & *energy detection*

2.1 De-chirping

This is removing the chirp to yield a signal with linear phase and so constant frequency. De-chirping is multiplying the received chirped baseband signal with the conjugate of the basic chirp (if basic chirp is up-chirp, the conjugate is down-chirp, and vice versa). Figure 3 tries to visualize this process.

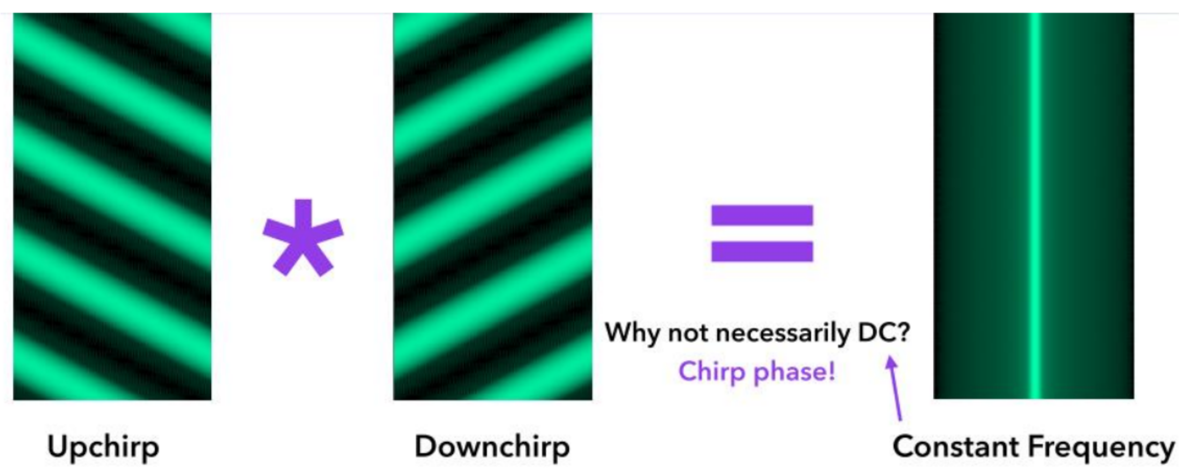

Figure 3: The de-chirping operation [1]

2.2 Energy detection

Here, the goal is detecting the peak energy of each de-chirped signal to determine the transmitted symbol at specific period. Ideally, this is easy as there will always will be a clear peak from the spectrum of the signal when $SNR = 0$. But for a corrupted signal with a very small SNR values, more processing is required.

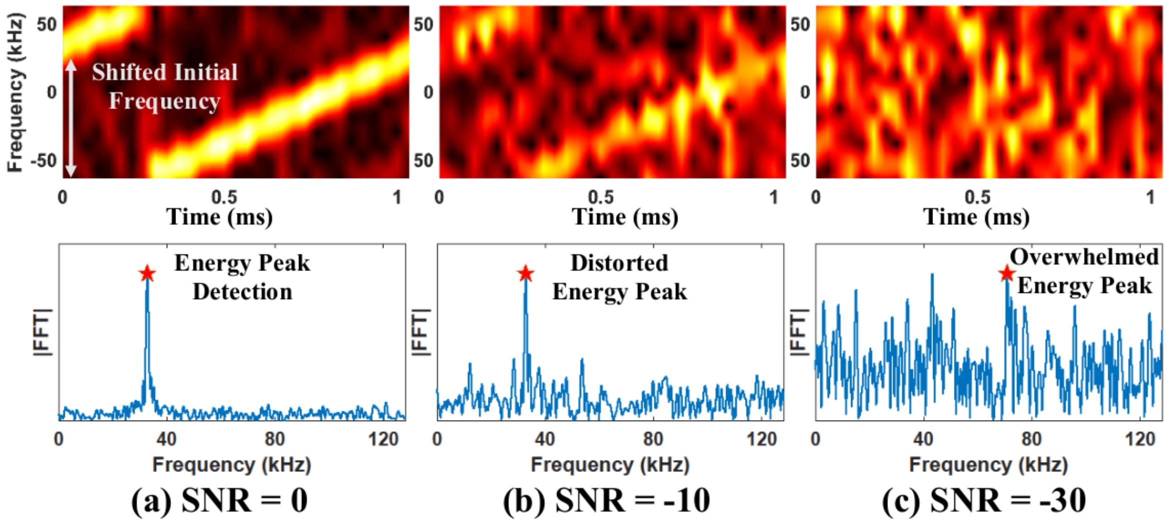

Figure 4: Spectrogram & spectral analysis result to detect the peak energy levels as SNR changes [2]

Since the received signal is random, which is usually modelled as Gaussian, *matched filter or coherent* receiver need to provide a normalized signal symbol that would be compared to a predetermined decision level signal o reference.

References

[1] Matthew Knight. Decoding lora a wireless network for the internet of things. In *RSA Conference*, page 118, 2017.

[2] Chenning Li, Hanqing Guo, Shuai Tong, Xiao Zeng, Zhichao Cao, Mi Zhang, Qiben Yan, Li Xiao, Jiliang Wang, and Yunhao Liu. Nelora: Towards ultra-low snr lora communication with neural-enhanced demodulation. In *Proceedings of the 19th ACM Conference on Embedded Networked Sensor Systems*, pages 56–68, 2021.

[3] Tung T Nguyen, Ha H Nguyen, Robert Barton, and Patrick Grossetete. Efficient design of chirp spread spectrum modulation for low-power wide-area networks. *IEEE Internet of Things Journal*, 6(6):9503–9515, 2019.

[4] AN Semtech. 120022, lora modulation basics, may, 2015, 2017.