

Signals and Systems II

Part V: Frequency conversion

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This six-part series is a mini-course, focused on system concepts, that is aimed at the gap between Signals and Systems and the usual first DSP course.

Part IV discussed analog and DSP-based IQ demodulation. This fifth article in the series is about frequency conversion and its use in larger systems. Figures are numbered in one sequence across the entire series, and gaps appear in their numbering in some individual articles. Figures are posted for instructional use on the author's website:

<http://alum.mit.edu/www/jeffc>

PART V

Frequency-conversion concepts

As the passband frequency becomes higher, either in absolute terms or relative to signal bandwidth, accurate modulation or demodulation directly from baseband to or from that passband frequency eventually becomes uneconomic. The standard solution adds one or more stages of analog *frequency conversion* to the passband part of the system to move the signal to/from baseband via one or more intermediate frequencies. The signal remains in real bandpass form at each stage, but with different carrier or center frequencies as pictured in Fig. 28. The terms modulation and demodulation then refer only to the steps that involve baseband signals. In Fig. 28 modulation and demodulation are the first and last steps respectively.

Frequency-conversion culture has evolved for two-thirds of a century and so is both rich with terms and powerful in insisting on their correct use. An *up-converter* does *upconversion*; it moves

spectral content further from the origin. A *downconverter* does *downconversion*, the reverse. The noun *IF*, or I.F. in older works, is pronounced “eye eff” and can either refer to a part of the system or to the nominal center frequency of the signal band that it passes. It is both adjective and noun, so it is perfectly acceptable to speak of the frequency of signals in the IF as the “IF frequency.” Multiple IF’s in a signal path are numbered ordinally in the direction of signal flow: first IF, second IF, etc.

The portion of the signal path opposite the baseband, beyond all the frequency conversions, is often labeled with the adjective *RF*, or R.F. in older works, particularly when an antenna or transmission line is only an amplifier and/or a filter away from it. As a noun RF most often means RF signal. RF is also used in a much broader sense: RF systems engineering as a discipline addresses all manner of systems that involve signals at frequencies typical of those put through transmission lines and antennas. RF is no longer an abbreviation for its historical referent, radio frequency, so “RF frequency” is perfectly acceptable.

Every frequency conversion conceptually requires certain basic steps, illustrated in spectral sketches in Fig. 29 and with an augmented state diagram in Fig. 30. The given input and the desired output each comprise a conjugate pair of spectral components located symmetrically on either side of the origin, but the distance of these components from the origin is to be changed by the conversion.

The strategy is to *filter* to select just one component of the input pair, *shift* that component in frequency to make it one component of the output

pair, and then add the conjugate to create the other half of the output pair. Different frequency-converter types result depending on whether filtering or shifting comes first and the type of filter used. Adding the conjugate always comes last conceptually, but it is sometimes moved in the realization.

In frequency-converter realizations, the noun *LO*, or sometimes L.O., refers either to any sinusoid at the shift frequency or to the device that creates such a sinusoid. LO may be used as an adjective, must be pronounced “ell oh”, and is still considered an abbreviation for “local oscillator,” from which it historically derives. The LO is said to be *high-side* or *low-side* according as the kept signal component is shifted across the origin or not. This definition implies that a high-side LO *spectrally inverts* the converted signal as shown in Fig. 29(b): the parts of the signal spectrum that began closer to the origin become the ones further away, and vice versa.

Image-rejection/phase-shift methods

In frequency conversion the presence of labels like *image-rejection* or *image-suppression* or *image-canceling* almost always implies the use of an analytic filter that both selects the desired half of the conjugate input pair and prevents image creation when the conjugate is added later. The Fig. 31 downconverter with a low-side LO illustrates. Such all-analog shift-then-filter downconverters appear occasionally in microwave systems, which use RF frequencies above roughly 1 GHz, and are typically structured as a separate LO and a prepackaged analog *image-rejection mixer*. Difficulties in getting adequate stopband rejection limit their popularity.

Analytic filters in microwave systems are traditionally camouflaged with hardware descriptions that neglect to mention that certain pairs of voltages should be thought of as complex signals for analysis purposes. When one of the ideal analytic filters of Fig. 19 from Part III, reproduced here, is given a real input, the real part of the output is related to the input by a simple gain. The imaginary part, however, is the result of passing the input through a type of allpass filter termed a *Hilbert transformer*. RF systems engineers seldom admit to implementing analytic filters and are often unfamiliar with the term, but they often admit to using Hilbert transformers or, in their very hardware-oriented terminology, 90° phase shifters.

When hearing of clever Hilbert-transformer phase-shift schemes to make things cancel, one should remember that most filters suppress signals in their stopbands using cancellation, so there is less to the distinction between filtering and cancellation than there appears to be. Certainly a filtering perspective provides a simpler understanding of such systems.

Classic frequency conversion

Until now, signals have been represented in the frequency domain with sketches of real functions having particular shapes that are certainly allowable as spectra but that are not very realistic. They are actually symbols rather than examples. This becomes more explicit in Fig. 32, where the function aspect is temporarily abandoned to reduce our effort in keeping track of which signal is which.

The system in Fig. 32 is the classic downconverter that comprises a frequency shift followed by a real bandpass *IF filter*. Recall (Part III) that conjugate addition can always be swapped with an adjacent real operation. This is used on the right in Fig. 32 to move conjugate addition to the earliest spot possible. The combination that results, frequency shifting a real input and then adding the conjugate, is always realized as a unit. Figure 16 shows why: together they apply *cosine modulation*, the multiplication of a real input by

a sinusoid, which multiplication is approximated in practice with an analog mixer.

The mixer introduces spurious terms here just as in Fig. 25 from Part IV, reproduced here, but here Wrong Way Corrigan of Fig. 25—our nickname for the spectral line at the negative of the desired LO frequency—is of no concern because the grouped operation on the right in Figure 16 lands the dominant, desired spectral impulse right on top of him and so ends his career.

The Fig. 32 downconverter is vulnerable to images as well as to mixer spurs. Comparison with the image-rejection downconverter in Fig. 31 reveals that this is the price of simplicity: the real IF-filter impulse response here corresponds to a conjugate-symmetric frequency response, so the desired signal cannot be passed without also passing an image. The solution is to make sure the image is suppressed by filtering prior to the downconverter.

In downconversion, keeping signal and image well separated for easy image suppression requires avoiding extreme ratios of input and output frequencies. This is why sequential downconversions are often used. In such systems the IF filter of the first downconversion typically handles image rejection for the second downconversion, so extra filtering specifically for image suppression, so-called *preselection* filtering, is generally needed ahead of the first downconversion only, in the RF stage.

It is interesting that with no preselection filter there is complete symmetry between signal and image. The system in Fig. 32 can be said to downconvert the **Blue Note** signal with a low-side LO and suffer the **Pink Floyd** signal as an image, or it can be said to downconvert the **Pink Floyd** signal using a high-side LO and with the **Blue Note** signal as an image. The ambiguity is only resolvable through image-rejection filtering to eliminate one or the other at the input.

The art of receiver design is very well developed, and frequency conversion is at its heart, determining basic receiver structure. The substantial

signal amplification typically required is usually distributed among IF stages and often, to some modest extent, the RF stage as well. The need for selectivity, selecting a narrowband input signal and thoroughly rejecting signals at nearby frequencies, for example in your cell phone, leads to IF filters that are the chambers of horror of the signal world: the whole band of signals goes in, but only one signal comes out! The lucky survivor is steered into the IF filter's passband using a digitally tunable LO, a *frequency synthesizer*, that fixes the amount of the frequency shift.

Relationships between input band-edges and IF frequencies and LO tuning ranges are carefully chosen so that tunable analog filters, which are rarely practical, are not required, so that images are always rejected adequately, and so that spurious signals from mixer harmonics are rejected by IF filters. Complications in meeting such constraints sometimes even leads to receivers that upconvert signals to a first IF above the signal band and then downconvert them to a second IF below the signal band for demodulation.

Upconverters with the classic Fig. 32 structure are also quite common, and while technically they have image frequencies, images are seldom a problem. (Draw a sketch. See why.)

Part VI will continue with discussions of two topics: first, vestigial-sideband modulation as a example system of significant complexity and, second, changing a sample rate by a rational but nonintegral ratio.

Read more about it

Frequency conversion, or the superheterodyne receiver structure in which it is used, is discussed in essentially all texts on communication systems, including Lathi. And of the many papers on image-rejection conversion, Crols and Steyaert is one of the more tutorial.

B. P. Lathi, *Modern Digital and Analog Communication Systems*, 3rd ed. Oxford University Press: www.oup.com, 1998.

J. Crols and M. S. J. Steyaert, "Low-IF topologies for high-performance analog front ends of fully integrated receivers," *IEEE Trans. Circuits and Systems II*, vol. 45, no. 3, Mar. 1998.

About the author

Jeffrey O. Coleman (S'75–M'79–SM'99) joined the Radar Division

of the Naval Research Laboratory (NRL) in Washington DC in 1978 then left it in 1985 for graduate studies, for a stint with The Boeing Company, and for a faculty position at Michigan Technological University from which he returned to NRL in 1997. His 1975/1979/1991

SBEE/MSEE/PhD degrees are from the Massachusetts Institute of Technology, Johns Hopkins University, and the University of Washington respectively, and his research is on theory and design methods in DSP. More: <http://alum.mit.edu/www/jeffc>

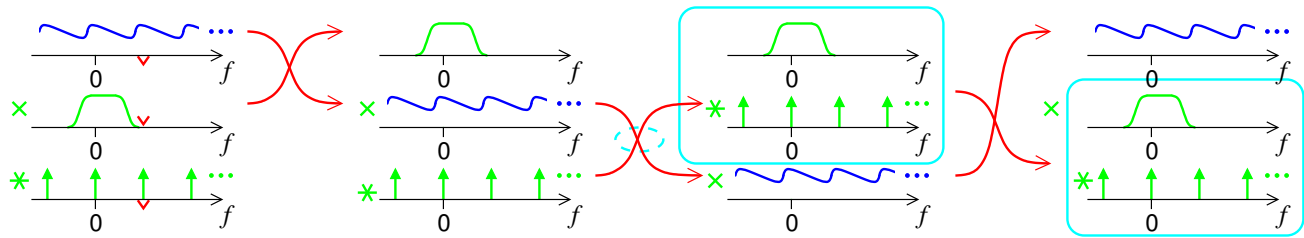


Fig. 14 (from Part II) The *most noble identity* (center) and product reordering (other red arrows) permit the top-to-bottom order of operations to be altered according to the *parenthetical groupings* and lead, on the right, to the Nyquist criterion.

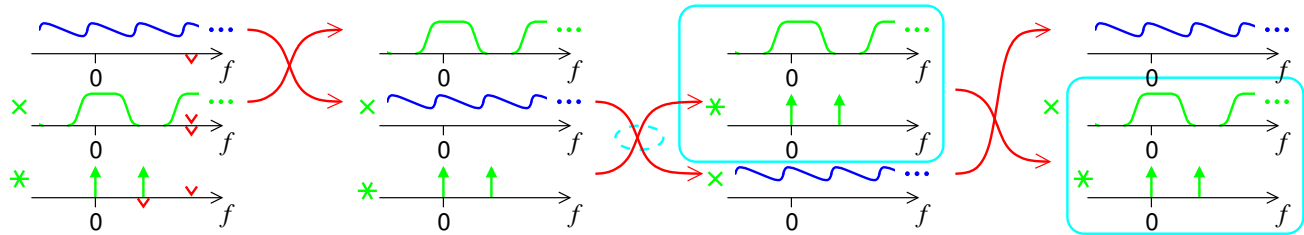


Fig. 15 (from Part IV) Only one even-numbered sample of a halfband filter's impulse response is nonzero, the sample at the origin. This derivation parallels that of Fig. 14 and in fact Nth-band and Nyquist filters are closely related.

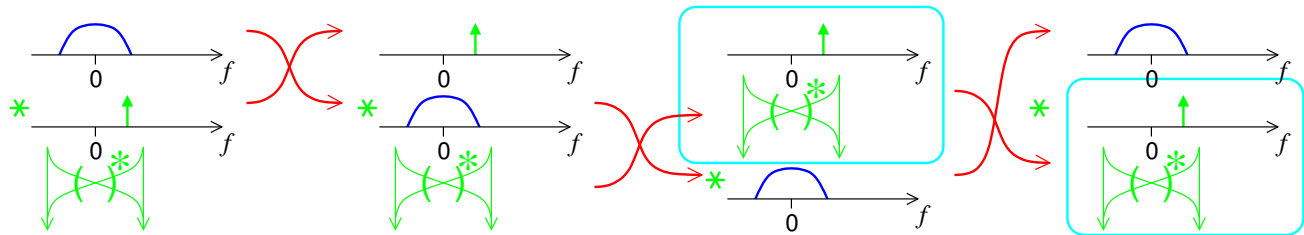


Fig. 16 Frequency shifting and then adding the conjugate to a real signal is equivalent to (and realized as) cosine modulation.

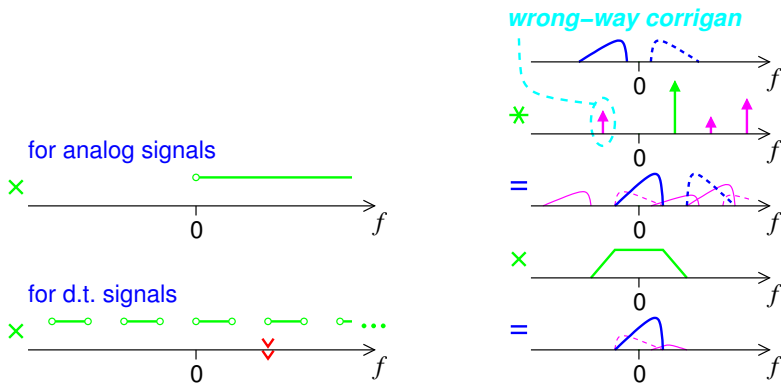


Fig. 19 (from Part III) The ideal analytic filters that define the most common notions of analytic signals.

Fig. 25 (from Part IV) In analog demodulators, spurious *harmonics* in the frequency shifting lead to spurious output terms.

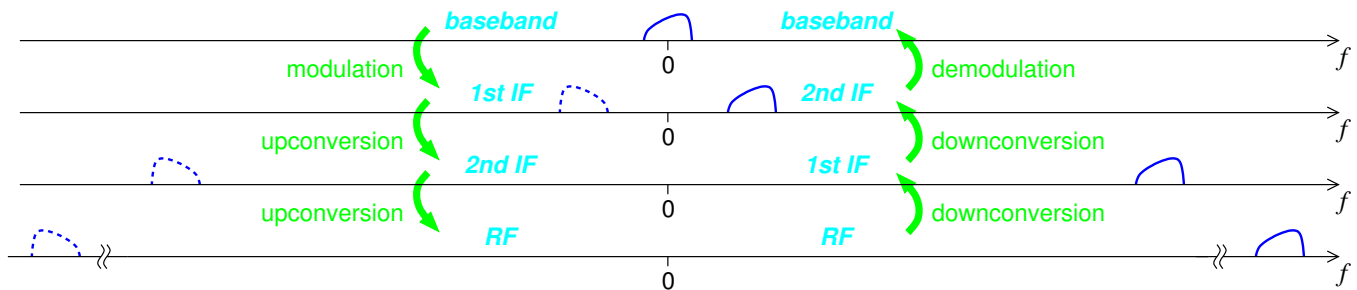


Fig. 28 Frequency conversion to one or more IF frequencies simplifies multistage modulation to (terminology on left) or demodulation from (terminology on right) higher frequencies.

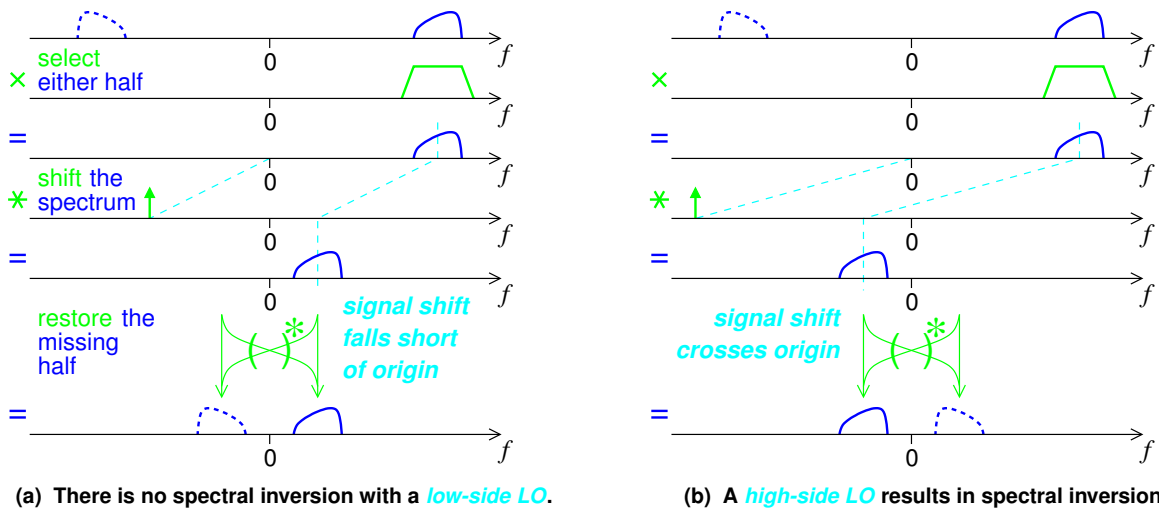


Fig. 29 Every upconverter or downconverter uses these three operations, but the first two can be in either order and the filter type can vary.

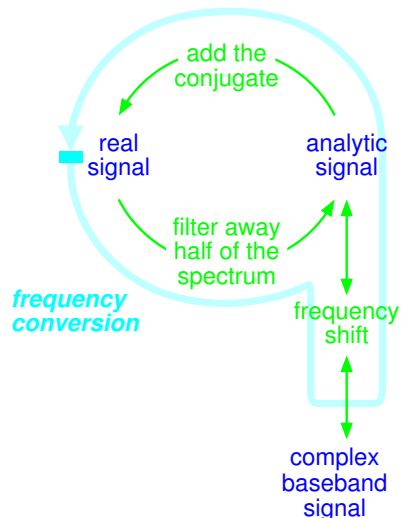


Fig. 30 All frequency conversions conceptually require filtering, shifting, and adding the conjugate, but the order may be varied from that shown.

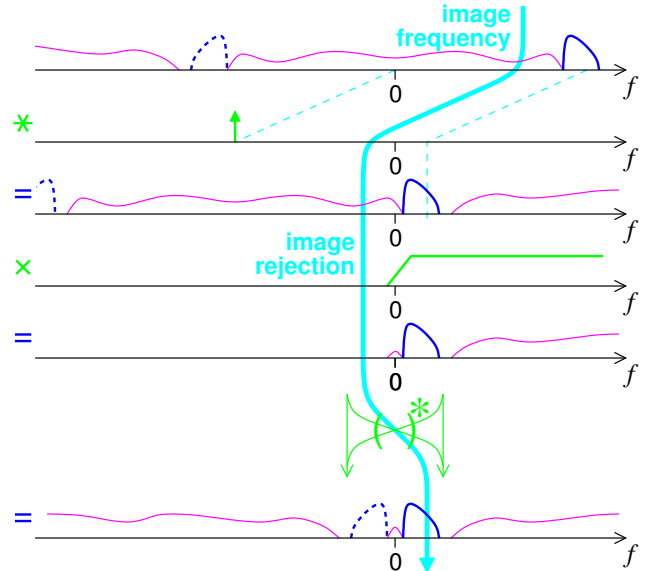


Fig. 31 Image-rejection conversion uses analytic filtering, typically at the lower (closer to the origin) frequency, either after the shift for downconversion (pictured) or before the shift for upconversion.

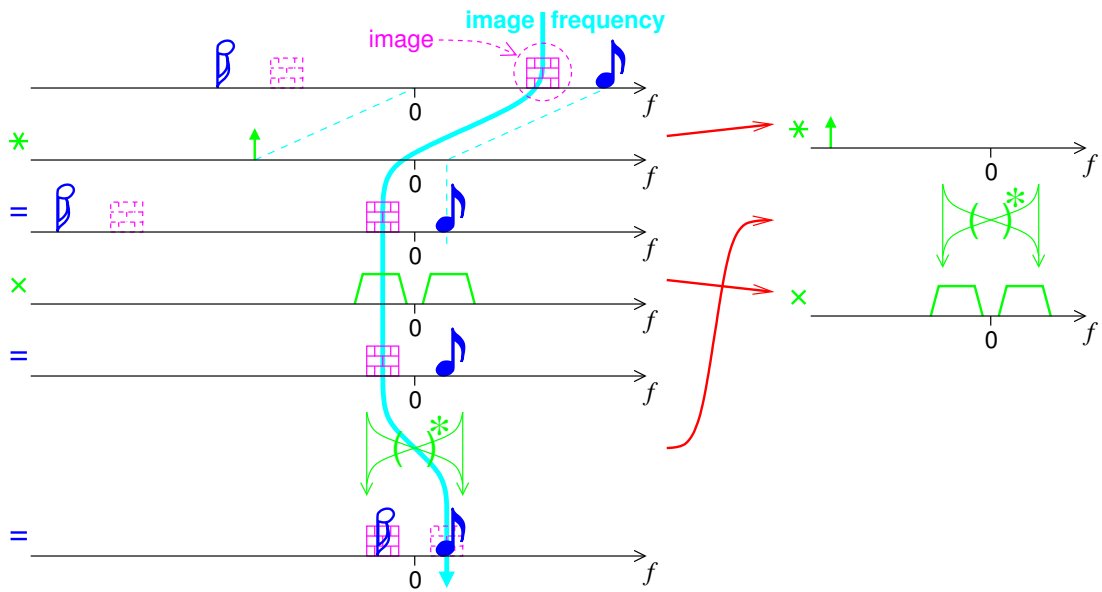


Fig. 32 The real impulse response in classic shift-and-filter downconversion makes it easy to realize in analog hardware, but it is image prone: without a preselection filter our jazz live from the Blue Note may drown under Pink Floyd rock.