I-Q Demodulator

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- Big Picture. 3 elements of communication systems
  - Tx
  - Channel
  - Rx: $\leftarrow$ We are here.

- Review. The complex envelope of the transmitted signal contains all the information about the message. This signal passes through a channel that is often, but not always, modeled by an LTI system. In either case, the received signal is well modeled by a real-valued bandpass signal whose complex envelope contains all the (degraded) information about the message.

- Preview. **Demodulation** can be understood as an operation that **extracts the complex envelope** of the desired bandpass part from the received signal. In particular, **an I-Q demodulator** is **a one real-valued bandpass input and two real-valued baseband output system** that recovers the real and the imaginary parts of the complex envelope.

- Received Signal Model
  - The signal $y(t)$ received by an antenna consists in general of a desired signal, interference, and noise.

$$y(t) = x(t) + I(t) + N(t).$$

    * If the noise is dominant, then the system is called power limited. Deep space communication system is power limited.
    * If the interference is dominant, then the system is called interference limited. Cellular communication system is interference limited.
    * The desired signal $x(t)$ is a real-valued bandpass signal with center frequency f_c and bandwidth W in passband.
    * Fig.

* The interference comes from, e.g., other communication systems. In this case, it is a summation of real-valued bandpass signals. There are roughly two types of such an interference.
  - co-channel interference (CCI): assumed not present in this course but omnipresent in cellular telecommunication systems
  - adjacent channel interference
  - Fig.

* The noise is usually modeled by an additive white Gaussian random process.
* Of course, there are other types of interference and models of noise.

– Why noise?

  * Interference is often modeled as a (part of the) noise.

  * At the Tx, the signal is amplified before it is fed to the Tx antenna.
    - Tx: transmitter, transmit
    - power amplifier (PA)
    - Tx nonlinearity may be modeled by an additive noise.

* The power level of the desired part of the received signal is often -150 dB below that of the transmitted signal.

$$10^{\frac{-150}{10}} = 10^{-15}$$

* Fig.

* This level of the signal power may not directly drive the signal processing circuit. So, the received signal needs to be amplified and then processed.
* However, we do not want to amplify all of the interference.
* Thus, as a compromise, we first roughly filter the received signal and then amplify.

- Rx frond end
  - Fig.

  - antenna
    - An antenna converts EM wave to current.
    - An antenna also serves as a part of pre-selection filter.
    - An antenna also serves as a part that generates noise.
  - pre-select filter, pre-selection filter
  - low noise amplifier (LNA)
    - multiple stages of amplifiers and filters
  - Fig. In FD, ...

- Q. Given $y(t) = x(t) + I(t) + N(t)$, extract $x_l(t)$ by using all real-valued input real-valued output operations.
  - For simplicity, we ignore noise.
  - For simplicity, we assume that $x(t)$ is the channel filtered version of the transmitted signal.
    * $y(t) = x(t) + I(t)$
    * Fig. In FD, ...

- Simplify. Ignore all real-valued operations constraint. Then, in FD, ...

– Fig. A real-valued input and complex-valued output down-conversion receiver

– The LPF is designed to pass only the desired signal part.

– Then,

$$x_l(t) = \mathrm{LPF}\{y(t) \cdot 2e^{-\mathrm{j}(2\pi f_c t + \phi)}\}$$

is a complex envelope of the desired signal part with phase ambiguity.

– Hinted by this solution to a simplified problem, we need to find all real-valued I/O receiver.

- A.
  - Since $x_l(t) = x_c(t) + \mathrm{j}x_s(t)$,

$$x_c(t) = \mathrm{Re}\{\mathrm{LPF}\{y(t) \cdot 2e^{-\mathrm{j}(2\pi f_c t + \phi)}\}\}$$

    and

$$x_s(t) = \mathrm{Im}\{\mathrm{LPF}\{y(t) \cdot 2e^{-\mathrm{j}(2\pi f_c t + \phi)}\}\}.$$

  - Note that, if the LPF has a real-valued impulse response $g(t)$,

$$\begin{aligned} x_c(t) &= \mathrm{Re}[\mathrm{LPF}\{y(t) \cdot 2e^{-\mathrm{j}(2\pi f_c t + \phi)}\}] \\ &= \mathrm{Re}[g(t) * \{y(t) \cdot 2e^{-\mathrm{j}(2\pi f_c t + \phi)}\}] \\ &= g(t) * \mathrm{Re}\{y(t) \cdot 2e^{-\mathrm{j}(2\pi f_c t + \phi)}\} \\ &= g(t) * \left[y(t) \cdot \mathrm{Re}\{2e^{-\mathrm{j}(2\pi f_c t + \phi)}\}\right] \\ &= \mathrm{LPF}\{y(t) \cdot 2\cos(2\pi f_c t + \phi)\}. \end{aligned}$$

  - Similarly,

$$x_s(t) = \mathrm{LPF}\{y(t) \cdot (-2\sin(2\pi f_c t + \phi))\}.$$

– Fig.

* This linear system is called **an I-Q demodulator, an I/Q demodulator, or a quadrature demodulator.**
* The system consists of all real-valued I/O subsystems.
* There is a negative sign in the quadrature branch as in the direct up-conversion transmitter.
* The system is a linear system but not time invariant. (Why?)
* A receiver having an I-Q demodulator is called **a direct down-conversion receiver or a homodyne receiver.**