Angle Modulation

- Time-varying frequency
- Introduction to angle modulation
- Relationship between FM and PM
- FM bandwidth

Many signals have time-varying frequency distributions (music, speech, video). Visualizations of time-varying frequency:
  - spectrogram
  - spectrum analyzer
  - graphics equalizer
Spectrogram

This spectrogram shows a *whistler* in the VLF band.
Spectrum Analyzer
Spectrum Analyzer (cont.)
Graphic Equalizer
**Instantaneous Frequency**

- In general, the frequency of a signal at an instant in time depends on the entire signal (Hilbert transform).

- For generalized sinusoids, we can use a simpler approach. Suppose

  \[ \varphi(t) = A \cos \theta(t). \]

  Then \( \theta(t) \) is the *generalized angle*. For a true sinusoid,

  \[ \theta(t) = \omega_c t + \theta_0, \]

  linear with slope \( \omega_c \) and offset \( \theta_0 \).

- The generalized angle is *not* limited to \([0, 2\pi]\). Wrapping introduces discontinuities.

- **MATLAB** has `unwrap` function to remove discontinuities.
Instantaneous Frequency (cont.)

- Instantaneous frequency is derivative of generalized angle:

\[ \omega_i(t) = \frac{d\theta}{dt} = \theta'(t) \]

- By Fundamental Theorem of Calculus,

\[ \theta(t) = \int_{-\infty}^{t} \omega_i(u) \, du = \omega_i(0) + \int_{0}^{t} \omega_i(u) \, du \]

- We can modulate a generalized sinusoid by using a signal \( m(t) \) to vary either \( \theta(t) \) or \( \omega_i(t) \).

- In either case, the frequency of the modulated signal changes as a function of \( m(t) \).
Instantaneous Frequency (cont.)

\[ \theta(t) \]

\[ \omega_c t + \theta_0 \]

\[ \Delta t \]

\[ t_1 \quad t_2 \]
Phase Modulation (PM) & Frequency Modulation (FM)

- In PM, phase is varied linearly with $m(t)$:

  $$\theta(t) = \omega_c t + k_p m(t) \implies \varphi_{PM}(t) = \cos(\omega_c t + k_p m(t))$$

  The instantaneous frequency is

  $$\omega_i(t) = \frac{d\theta}{dt} = \omega_c + k_p \dot{m}(t)$$

  If $m(t)$ varies rapidly, then the frequency deviations are larger.

- In FM, frequency deviation is linear in $m(t)$:

  $$\omega_i(t) = \omega_c + k_f m(t)$$

  The angle is

  $$\theta(t) = \int_{-\infty}^{t} (\omega_c + k_f m(u)) \, du = \omega_c t + k_f \int_{-\infty}^{t} m(u) \, du$$
Relationship Between FM and PM

- Phase modulation of \( m(t) = \) frequency modulation of \( \dot{m}(t) \).
- Frequency modulation of \( m(t) = \) phase modulation of \( \int m(u) \, du \).

- Diagrams showing the relationship between phase modulation and frequency modulation.
Generalized Angle Modulation

- We can vary phase using a linear transform of message signal:

\[ \varphi_{EM}(t) = A \cos(\omega_c t + h(t) \ast m(t)) \]

\[ = A \cos(\omega_c t + \int_{-\infty}^{t} m(u)h(t - u) \, du) \]

Note that the impulse response \( h(t) \) is causal.

- PM \((h(t) = k_p \delta(t))\) and FM \((h(t) = k_f u(t))\) are special cases.

- We recover \( m(t) \) from phase by using inverse filter \( H^{-1}(s) \).
  E.g., for FM the inverse of integration is differentiation.
FM Example: \( k_f = 2\pi \times 10^5, f_c = 100 \text{ MHz} \)

\[ f_i = f_c + \frac{k_f}{2\pi} m(t) = 10^8 + 10^5 m(t) \]

\[ f_{i,\text{min}} = 99.9 \text{ MHz} \]
\[ f_{i,\text{max}} = 100.1 \text{ MHz} \]

Is the modulated signal confined to the frequency band \( 99.9^- - 10.1^+ \)?

No. The bandwidth is approximately 300 KHz.
PM Example: $k_p = 10\pi, f_c = 100$ MHz

Instantaneous frequency:

$$f_i = f_c + \frac{k_p}{2\pi} \dot{m}(t) = 10^8 + 5\dot{m}(t)$$

$$f_{i,\text{min}} = 99.9 \text{ MHz}$$

$$f_{i,\text{max}} = 100.1 \text{ MHz}$$

FM modulation of $m(t)$ is same as PM modulation of $\dot{m}(t)$. 
Frequency Shift Keying (FSK)

The binary message can be detected using two filters tuned for the two frequencies.

FSK is a historically important digital modulation scheme. The Bell 103 modem used frequencies 1070 and 1270 for originating station.
Phase Shift Keying (PSK)

The binary message can be detected by correlating with sinusoids of a fixed frequency but different phases.

The sinusoids are $180^\circ$ out of phase but synchronized with the carrier.
PSK: Direct Modulation

If $k_p = \pi/2$ and $m(t)$ takes on only values $+1$ and $-1$, then

$$\varphi_{FM}(t) = A \cos(\omega_c t + k_p m(t))$$

$$= A \cos(\omega_c t + \frac{\pi}{2}m(t))$$

$$= \begin{cases} 
A \sin \omega_c t & \text{when } m(t) = -1 \\
-A \sin \omega_c t & \text{when } m(t) = 1 
\end{cases}$$

The figure on the previous slide corresponds to bit duration $7/f_c$, where $f_c$ is the carrier frequency.

Phase changes of $\pm \pi$ are possible at the end of each bit period.

The transmitter must low pass filter the PSK signal.