Sachin Katti is an Assistant Professor of Electrical Engineering and Computer Science at Stanford University. His research focuses on designing and building next generation high capacity wireless networks by combining techniques from information and coding theory, RF systems, and networking. He is also the Co-Founder and ex-CEO of Kumu Networks which is commercializing his research on full duplex radios: radios that can transmit and receive signals simultaneously through self-interference cancellation. The technology is broadly applicable across all radios; Kumu is developing products that use full duplex technology to significantly improve cellular spectral efficiency and broadband speeds. He is also currently working with Google.org to transfer his research on OpenRadio and software defined cellular networking to practice via a broadband network deployment in Northern California. The goal is to create open, inexpensive and re-usable network hardware and software substrates that underserved communities around the world can use to quickly deploy broadband wireless networks.

Professor Katti received his PhD in EECS from MIT in 2009. His research has won numerous awards, including the 2008 ACM Doctoral Dissertation Award - Honorable Mention, the George Sprowls Award for Best Doctoral Dissertation in EECS at MIT, the IEEE William Bennett Prize, the Best Student Paper Award at ACM SIGCOMM 2012, USENIX ATC 2013, the Sloan Fellowship, the NSF Career Award as well as Okawa, Hooover, Packard and Terman Faculty Fellowships.
Review of Last Lecture

- **Digital Downsampling**
  - Removes samples of $x(nT_s)$ for $n \neq MT_s$
  - Repeats $X_d(e^{j\Omega})$ every $2\pi/M$ and scales $\Omega$ axis by $M$
  - Can prefilter $X_d(e^{j\Omega})$ by LPF with bandwidth $\pi/M$ prior to downsampling to avoid downsample aliasing

- **Communication System Block Diagram**

  ![Block Diagram](image)
Review of Friday’s Lecture

**DSBSC, SSB, Broadcast AM**

- **(DSBSC)** Modulated signal is \( s(t) = m(t) \cos(\omega_c t) \)
  - Signal bandwidth (bandwidth occupied in positive frequencies) is 2W
  \[
  s(t) = m(t) \cos(\omega_c t) \iff .5[M(j(\omega - \omega_c)) + M(j(\omega + \omega_c))]
  \]

- Redundant information: can either transmit upper sidebands (USB) only or lower sidebands (LSB) only and recover \( m(t) \)
  - Single sideband modulation (SSB); uses 50% less bandwidth (less $$)$$

- Demodulator for DSBSC/SSB: multiply by \( \cos(\omega_c t) \) and LPF

- **Broadcast AM** has \( s(t) = [1+k_\alpha m(t)] \cos(\omega_c t) \) with \( [1+k_\alpha m(t)] > 0 \)
  - Can recover \( m(t) \) with envelope detector (see lecture 12 of 102a notes)
Quadrature Modulation

Sends two info. signals on the cosine and sine carriers

\[ m_1(t) \cos(\omega_c t) + m_2(t) \sin(\omega_c t) \]
FM Modulation

- Message signal $m(t)$ encoded in carrier frequency
- FM modulated signal:

$$s(t) = A \cos(\theta(t)) = A \cos(\omega_c t + k_f \int m(\tau) d\tau)$$

  - Instantaneous frequency: $\omega_i = \omega_c + k_f m(t)$
  - Signal robust to amplitude variations and reflections
  - Frequency analysis nonlinear (hard, will skip)

- Frequency Deviation: $\Delta f = k_f \max |m(t)|$
  - Maximum deviation of $\omega_i$ from $\omega_c$: $\omega_i = \omega_c + k_f m(t)$

- Carson’s Rule for bandwidth of $s(t)$:

$$B_s \approx 2\Delta f + 2B_m$$

  Depends on max deviation from $\omega_c$ and how fast $\omega_i$ changes

- FM Demod: Differentiator + Envelope Detector
Main Points

- **Modulation** is the process of encoding an analog message signal (or bits) into a carrier signal
  - DSBSC multiplies the message signal and the carrier together.
  - Synchronous demodulation multiplies by the carrier and then uses a LPF. Requires learning carrier phase at receiver (hard!)

- **SSB** is a spectrally efficient AM technique with half the BW requirements of standard AM and DSBSC.

- **Quadrature modulation** sends two different signals in the same bandwidth using sin and cosine carriers (which are orthogonal)

- **FM modulation** encodes information in signal frequency. More robust to amplitude errors and signal reflections than AM
  - Bandwidth depends on info. signal bandwidth and freq. deviation
Introduction to Digital Modulation

- Most information today is in bits
- Baseband digital modulation converts bits into analog signals \( y(t) \) (bits encoded in amplitude)

\[
y(t) = \sum_{k=-\infty}^{\infty} a_k \text{rect}(t - kT_b) = x(t)^* \text{rect}(t) \quad \text{for} \quad x(t) = \sum_{k=-\infty}^{\infty} a_k \delta(t - kT_b)
\]

- Pulse shaping (optional topic)
  - Instead of the rect function, other pulse shapes used
  - Improves bandwidth properties and timing recovery
Passband Digital Modulation

- Changes amplitude (ASK), phase (PSK), or frequency (FSK) of carrier relative to bits
- We use BB digital modulation as the information signal $m(t)$ to encode bits, i.e. $m(t)$ is on-off, etc.
- Passband digital modulation for ASK/PSK is a special case of DSBSC; has form

$$s(t) = \sum_{k=-\infty}^{\infty} m(t)\cos(\omega_c t)$$
ASD and PSK

- **Amplitude Shift Keying (ASK)**
  \[ s(t) = m(t) \cos(\omega_c t) = \begin{cases} A \cos(\omega_c t) & m(nT_b) = A(\text{"1"}) \\ 0 & b(nT_b) = 0(\text{"0"}) \end{cases} \]

- **Phase Shift Keying (PSK)**
  \[ s(t) = m(t) \cos(\omega_c t) = \begin{cases} A \cos(\omega_c t) & m(nT_b) = A(\text{"1"}) \\ A \cos(\omega_c t + \pi) & m(nT_b) = -A(\text{"0"}) \end{cases} \]
Main Points

- NBFM easy to generate and analyze. WBFM harder
- In theory just need differentiator and envelope detection for FM. Many techniques used in practice (mostly VCO).
- Digital baseband modulation encodes bits in analog signal, whose properties are dictated by the pulse shape
- Digital passband modulation encodes binary bits into the amplitude, phase, or frequency of the carrier.
- ASK/PSK special case of AM; FSK special case of FM