Low-Power Radio Design
Challenges and Solutions for Wearables

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Mojo Vision
Wearables Landscape

• Primary function: health monitoring, fitness tracking, information display, augmented reality
Trends in Wearable Devices

• Augmented/virtual reality -> Information display
  – Increases datarate

• Interaction
  – Additional sensors
  – Additional processing
  – Stringent latency requirement

• Invisible computing
Augmented-Reality Contact Lens

- Realtime display
- Content adjustment based on user’s gaze
- Battery life should extend to a full day
- Volume limitation
- Multi-user support

- Display
- Wireless transceiver
- Image sensor
- Motion sensors
- Batteries
- Passive components
Challenges of an AR Contact Lens

- **Size**
  - Limited volume for batteries
  - Smaller number of external components
  - Higher levels of integration

- **Power**
  - Energy harvesting still not at a point to sustain no-battery operation
  - Limited power necessitates processing being done elsewhere
  - Total power budget: a few mW

- **Wireless communication**
  - High datarate (>10Mbps)
  - Low latency round-trip
  - Tolerance to interference

Standard BLE or IoT approaches not enough!
No Universal Solution

• Every application has a unique solution

• What can we trade for power and size?
  – Datarate
  – Duty cycling
  – Spectral efficiency
  – Sensitivity
  – …

• Let’s first look at some fundamentals!
Modulation

\[ S_{RF} = A \cos(\omega t + \varphi) \]

- Can embed information in \( A \), \( \omega \) or \( \varphi \)

Phase only

Phase and amplitude

BPSK

QPSK

8PSK

4-QAM

8-QAM

16-QAM
Trade-offs

Quality of communication
Probability of Error

Ease of Recovery
Eb/N0 (Normalized SNR)

Spectral Efficiency
Normalized datarate

\[
\frac{E_B}{N_0} = \frac{\text{SNR}}{\text{SE}}
\]

\[
\text{SE} = \frac{\text{DR}}{\text{BW}}
\]
Trade-offs

Probability of error = $10^{-5}$
Summary of Modulation Schemes

• Higher order PSK and QAM more spectrally efficient at the expense of SNR and power

• PSK/QAM more practical for congested environments
  – Information in phase/amplitude costs little bandwidth

• M-FSK offers relaxed SNR at the expense of spectral efficiency → Good for sparse areas
Synchronous vs Non-Synchronous Communication

- Synchronous communication relies on knowledge of phase
  - Requires phase/frequency tracking loops (PLL, Costas, …)
  - Requires high-power blocks

- Non-synchronous communication
  - Envelop detection obviates the need for carrier generation
  - Does not need power-hungry LO generation
  - Much lower power
A Note on Envelop Detection

• Extreme low power comes at a cost

• Inherently non-discriminating across frequencies
  – Low datarate
  – Noise folding
  – Sensitivity to interference/blockers
  – Hard to get to work for multi-user situations

• Useful for wake-up receivers to enables efficient duty cycling
Survey of Existing Solutions

- Coherent detection consumes far more power
- Every 20dB in sensitivity saves 10x power

Leveraging the “Gateway”

- Most wearables are paired with a gateway device
  - Phone or a custom accessory device

- The gateway is less power/size constrained

- Complexity can be shifted to the gateway device
  - Leave energy-intensive processing to the gateway
  - Trade sensitivity for power on the wearable

- Wearables are inherently asymmetric
  - Much more data for Rx than Tx
So Far

• Picked coherent communication scheme based on datarate requirement

• Traded Rx sensitivity and Tx RF output power for system power leveraging the gateway

• What can we do at circuit level?
Where Does the Power Go?

- Any block operating at RF
- LO generation is particularly power hungry
Mixer-First Architectures

• Why LNA first?
  – Reduces noise contribution of subsequent stages
  – Reduces LO leakage to antenna
  – Often achievable performance limited by linearity requirement

• Why mixer first?
  – High out of band linearity (e.g., use passive mixer)
  – Can implement additional bandpass filtering (n-path)
  – Noise figure hit is manageable thanks to reduced sensitivity
Example

• Low-power passive mixer
• Additional bandpass-filtering due to mixer + baseband filter
• NF 5-12dB

B. W. Cook, et al., JSSC 2006

Also see RTu1H-2 and RTu1H-3
Reducing Clocking Power

- Efficient multiphase generation
- Eliminate/reduce LO distribution
- LO frequency reduction without changing carrier frequency
Quadrature Generation

- VCO + divider
- Better phase noise ✓
- Need an oscillator running at 2f₀
- Divider power

- Coupled VCOs
- No blocks running at higher than f₀ ✓
- Larger area
- Off-resonance operation degrades PN

Lo buffer power can easily dominate
Quadrature LO or Quadrature RF

- Quadrature in LO Domain
- Need to distribute 2 phases ×

- Quadrature in RF Domain
- Single LO phase ✓
- Higher loss in receive path ×
Sub-Harmonic Mixing

• Similar to harmonic-reject receiver
• LO at a subharmonic of the RF, e.g., $f_{LO} = \frac{f_{RF}}{2}$
• Need to strong harmonic content:
  – Non 50% duty-cycle
  – Or combine edges from multiple phases
Sub-Harmonic Mixing

- LO at one-third of RF (5.8GHz)
- Multiphase naturally available through ring oscillator
- NF of 14dB
- Power still dominated by LO generation
Direct RF Sampling Receiver

- Similar to software-defined radio
- Direct RF to baseband conversion
- Sampling clock at baseband frequency

H. Wang et al., JSSC 2020
Summary

• Emerging wearables fall in a less-explored space of low-power high-datarate design

• A gateway device can be leveraged to reduce power of the wearable

• Optimization needs to be done at both system and circuit levels to enable >10Mbps radios at mW power budget
Further Reading

- **Digital communication basics**

- **Survey of low power radios**

- **Mixer-first Receivers**
  - S. Huang, A. Molnar, “A 3.7–6.5GHz 8-Phase N-Path Mixer-First Receiver with LO Overlap Suppression Achieving 5dB NF and >5dBm OOB B1dB”, RFCI 2021, RTU1H-3

- **Rectifier-based Wake-up receivers:**
  - J. Im, et al., “A Fully Integrated 0.2V 802.11ba Wake-Up Receiver with -91.5dBm Sensitivity”, RFCIC 2020. [Link]

- **Coupled VCOs**

- **LC-VCO using an off-chip inductor**

- **Subharmonic mixing**

- **Subsampling receiver**

- **Interference tolerant Rx (not discussed in this presentation but relevant)**
Thank You

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