Polymorphic Radios: A new design paradigm for ultra-low power communication

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Why do we need a new low-power radio?
Evolving communication needs

Connectivity (circa 1995) → Streaming (circa 2015)
Evolving communication needs

Connectivity (circa 1995) → Streaming (circa 2015)
What about radio power consumption?

**Challenge**: Low-power radios optimized for sporadic rather than streaming communication.
What about radio power consumption?

**Goal**: Design a low-power streaming radio that provides low-latency connectivity and is reliable under dynamics.
How can we optimize a streaming radio?

<table>
<thead>
<tr>
<th>RX sensitivity</th>
<th>RSS (dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-92</td>
</tr>
<tr>
<td></td>
<td>-62</td>
</tr>
</tbody>
</table>

30dB gap
How do radios leverage the gap?

- Transmit quickly (aka duty-cycling)
- Transmit softly (aka power control)

RX sensitivity

RSS (dBm)

-92 -62

30dB gap

0 dBm

-30 dBm

active

sleep
How do radios leverage the gap?

Transmit softly (aka power control)

- 0 dBm
- -30 dBm

Oscillator
LNA/PA
Mixer

low efficiency at low output power

Transmit quickly (aka duty-cycling)
How do radios leverage the gap?

Transmit softly (aka power control)

State-of-art low-power active radio (Nordic nRF5):
- 16mW @ 0dBm
- 8mW @ -40dBm

Transmit quickly (aka duty-cycling)
How do radios leverage the gap?

Transmit softly (aka power control)

Transmit quickly (aka duty-cycling)

State-of-art BLE (Nordic nRF5):
- 16mW @ 0dBm
- 8mW @ -40dBm
How do radios leverage the gap?

Transmit quickly (aka duty-cycling)
- Faster ⇒ higher on-off overhead
- Shorter ⇒ less channel visibility

Transmit softly (aka power control)

State-of-art BLE (Nordic nRF5):
- 16mW @ 0dBm
- 8mW @ -40dBm

0 dBm
-30 dBm
Can we use passive radios?

Active Radios
- Bluetooth
- LoRa
- ZigBee

Oscillator
LNA/PA
Mixer

Passive Radios
- Backscatter TX
- Envelope Detector RX
Can we use passive radios?

**Active Radios**
- Bluetooth
- LoRa
- ZigBee

**Passive Radios**
- Oscillator
- LNA/PA
- Mixer
- Backscatter TX
- Envelope Detector RX

**Comparison**
- Power efficiency
- Reliability
How about passive radios?

Active Radios

\[ P_r \propto \frac{1}{d^2} \]

Passive Radios

\[ P_r \propto \frac{1}{d^4} \]
How about passive radios?

**Active Radios**

- RX
- LNA
- Sensitivity = -92dBm

**Passive Radios**

- Passive Rx
- Sensitivity = -50dBm

- Power efficiency
- Reliability
Key Challenge

Active RF

- reliable but inefficient

Passive RF

- efficient but unreliable
Key Challenge

Active RF

reliable but inefficient

Passive RF

efficient but unreliable
Polymorphic Radios

Polymorphic radios: Combine active and passive building blocks to design low-power streaming radios.
Two modes of operation

Active RF + Passive RF = active-assisted passive
Mode 1: Active-assisted Backscatter

Active Radio

Passive Radio

Received Signal Strength

Receive Sensitivity @ 100kbps
Mode 1: Active-assisted Backscatter

Active Radio

Passive Radio

Received Signal Strength
Two modes of operation

- Active RF
- Passive RF

- Active-assisted passive
- Passive-assisted active
Mode 2: Backscatter-assisted Active

Active Radio

Passive Radio

Rx sensitivity depends on energy-per-bit
Mode 2: Backscatter-assisted Active Radio

Active Radio

Passive Radio

Near-Zero Power Channel Measurement

RSS

@ 100kbps

@ 3kbps
Polymorphic radio in a nutshell

When passive works well, use active sparingly for reliability.

When passive works poorly, use to monitor channel and optimize active duty-cycling.
Roadmap: Network Stack

- Application: Streaming Video/Audio
- MAC: Radio Selection/Switching
- PHY: Polymorphic Radio HW
Hardware Overview

- PA
- LNA
- Fast Envelope Detector
- Slow Envelope Detector
- Tx Baseband
- Rx Baseband
- Channel Meas. Shift Reg.
- Backscatter Switch
- Splitter
Hardware Overview

Active Radio

Splitter

PA

LNA

Tx Baseband

Rx Baseband

Backscatter Switch

Channel Meas. Shift Reg.
Hardware Overview

Passive - Backscatter

Backscatter Switch

Channel Meas. Shift Reg.

Tx Baseband

Splitter

LNA

Rx Baseband

Fast Envelope Detector

Slow Envelope Detector
Hardware Overview

Passive - Envelope Detector

Fast Envelope Detector

Slow Envelope Detector
Hardware Benchmarks

## Mode Switching - Latency
- 30µs

### Active Mode
- 5.2mW @ 1.1dBm, 900MHz

### Backscatter Mode
- 10µW (measurement)
- 50µW (data)
MAC - Decision Engine

**Imputed RSS**

- TX mode
- TX bitrate
- RX mode
- RX bitrate

RSS measured in active mode

RSS measured in passive mode

\[ P(\text{RSS} > \text{RSS}_t \text{ in next } k \text{ slots} | \text{RSS}_t, \ldots, \text{RSS}_{t-10}) \]
## MAC Evaluation - Datasets

<table>
<thead>
<tr>
<th>Device</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wrist IMU</td>
<td>Streaming IMU data @ 100 samples/sec from a Smartwatch</td>
</tr>
<tr>
<td>Lapel Audio</td>
<td>Streaming audio @ 4kHz sampling rate from a Lapel accessory (dialog)</td>
</tr>
<tr>
<td>Eyeglass camera</td>
<td>Streaming video @ 30fps from low power camera on an eyeglass</td>
</tr>
</tbody>
</table>
Energy-efficiency vs. Reliability

Packet loss rate (%)

Energy efficiency (bits/nJ)

Backscatter

Duty-cycled Active
Energy-efficiency vs. Reliability

Polymorphic (5x better efficiency than active)
Goal: Demonstrate low-power yet high quality audio streaming using a polymorphic radio
Application: Audio Streaming

<table>
<thead>
<tr>
<th>Energy Efficiency (bits/nJ)</th>
<th>Mean Opinion Score (MOS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>Excellent</td>
</tr>
<tr>
<td>10</td>
<td>Good</td>
</tr>
<tr>
<td>1</td>
<td>Fair</td>
</tr>
<tr>
<td>0.1</td>
<td>Poor</td>
</tr>
<tr>
<td>0.1</td>
<td>Bad</td>
</tr>
</tbody>
</table>

Passive

Polymorphic (6x better efficiency than active)

Duty-cycled Active
Application: Video Streaming

**Goal:** Demonstrate tradeoff between sensing cost and communication cost using a polymorphic radio
**Goal**: Demonstrate tradeoff between sensing cost and communication cost using a polymorphic radio.
Passive radio has low cost, hence more energy is available for sampling, and vice-versa for active radio.
Application: Video Streaming

Dense sampling

Sparse sampling

Passive

Active

Active

Backscatter

Polymorphic

Pupil Tracking Error (pixels)
Conclusions

Combining active and passive architectures allows us to design low-power streaming radios.