# Improving Energy Efficiency of Wireless Communication Circuitry in Miscellaneous Electric Loads


- Performing Organization(s): University of Virginia, University of Michigan, ORNL
- PI Name and Title: Ben Calhoun, Professor, UVA
- Emails: bcalhoun@virginia.edu

# Project Summary

**Timeline:**

Start date: January 1, 2018

Planned end date: December 31, ~~2020~~ 2021

Key Milestones

1. Complete WiFi wakeup receiver and node controller IC design; 12/31/18
2. Measured IC results and application to MELs; 802.15.4 wakeup; 12/31/19
3. Integrated system reducing MELs phantom energy by 50%; ~~12/31/20~~ 12/31/21

**Budget:**

**Total Project $ to Date:**

- DOE: $1,982,361
- Cost Share: $260,439

**Total Project $:**

- DOE: $2,426,667
- Cost Share: $266,667

**Key Partners:**

| U. Michigan | ORNL |
|---|---|
| Everactive (was PsiKick) | Trane |
| UTRC | Johnson Controls |
| SkyCentrics | Samsung |

**Project Outcome:**

Develop a Connectivity Module to reduce MELs phantom energy by over 50% and idle energy by over 20%.

This module leverages custom integrated circuits for wakeup from WiFi at <1 mW and wakeup from NB-IoT at < 500 μW.

# Team

MELs Power State Management

Network and Integration

Custom Integrated Circuits

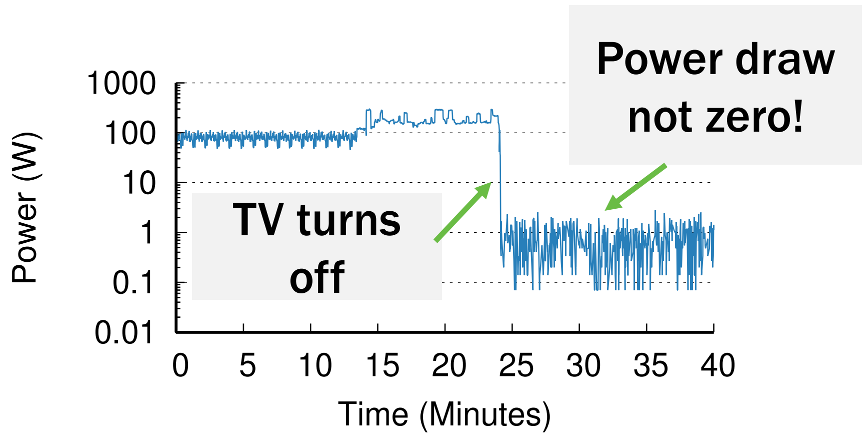
| University of Virginia | | U. Michigan | ORNL |
|---|---|---|---|
|  |  |  |  |
| Dr. Ben Calhoun | Dr. Brad Campbell | Dr. David Wentzloff | Dr. Teja Kuruganti |

Cross-hierarchical team to address MELs connectivity and efficiency

# Challenge

Many miscellaneous electric loads (MELs) consume phantom power when off simply to enable connectivity or to remain in standby mode. This small, yet continuous, power draw (typically 1-3 Watts) adds up, costing upwards of $30/year/home.

## TV Power Trace



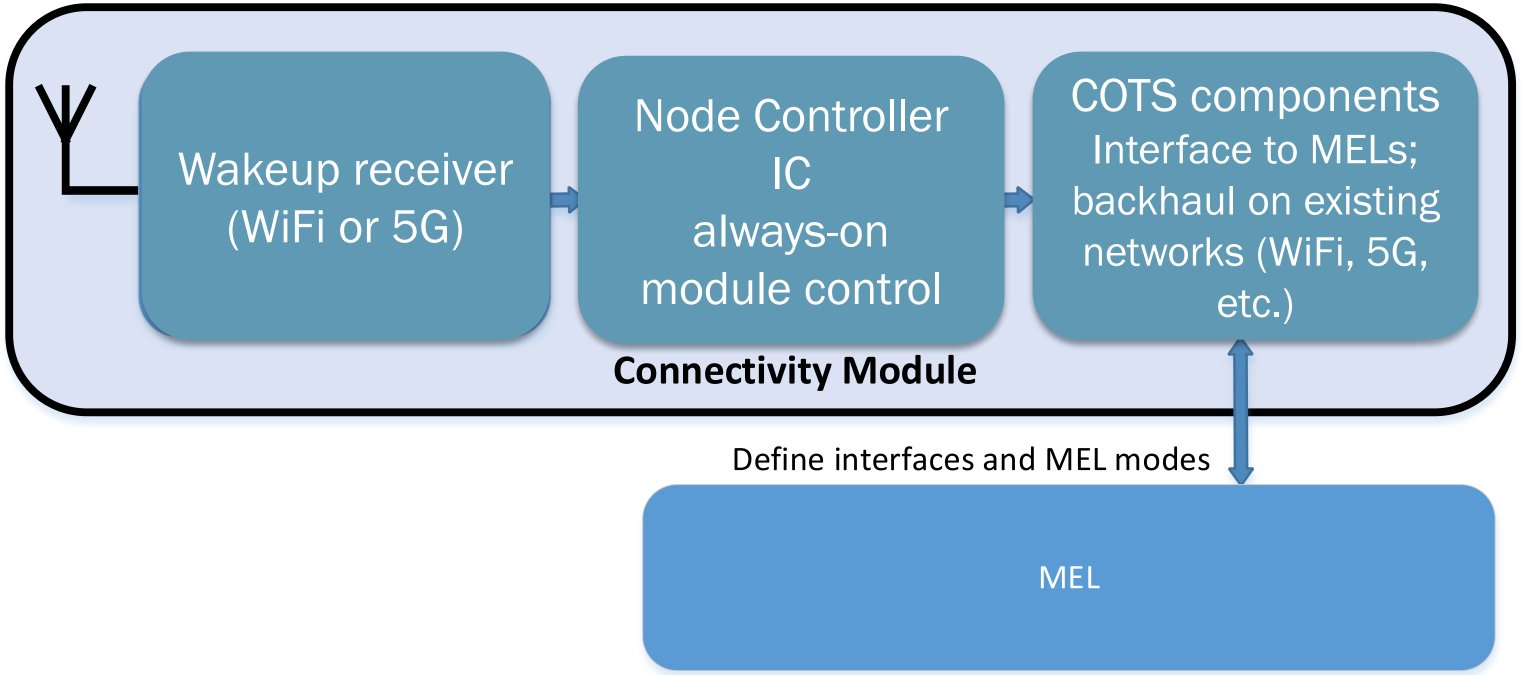

Ideally, when a MEL is switched off it would consume zero power.

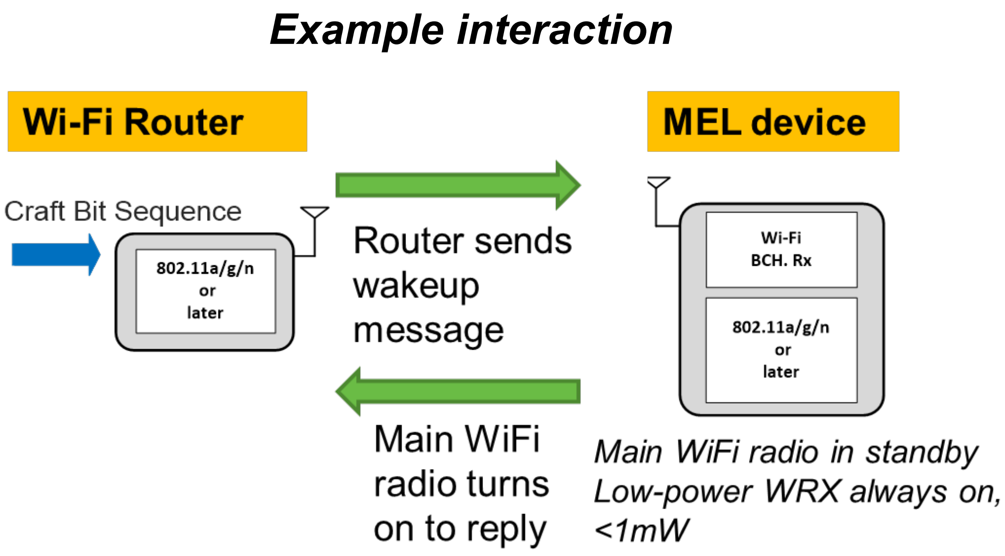
At a national scale MELs are…

- 30% of electricity in residential buildings
- 36% of electricity in commercial buildings

We propose leveraging advances in ultra-low-power wireless radios and smart control methods to cut phantom power consumption of MELs by 60-90%.

# Approach




- Custom radio frequency (RF) wakeup receiver (WRX) ICs for WiFi and 5G
- Custom ICs for MELs interfacing and continuous control
- Custom printed circuit board (PCB) for integration into Connectivity Module
- Wake on Wireless (WoW) capability
- MELs WoW and control optimization

# Impact

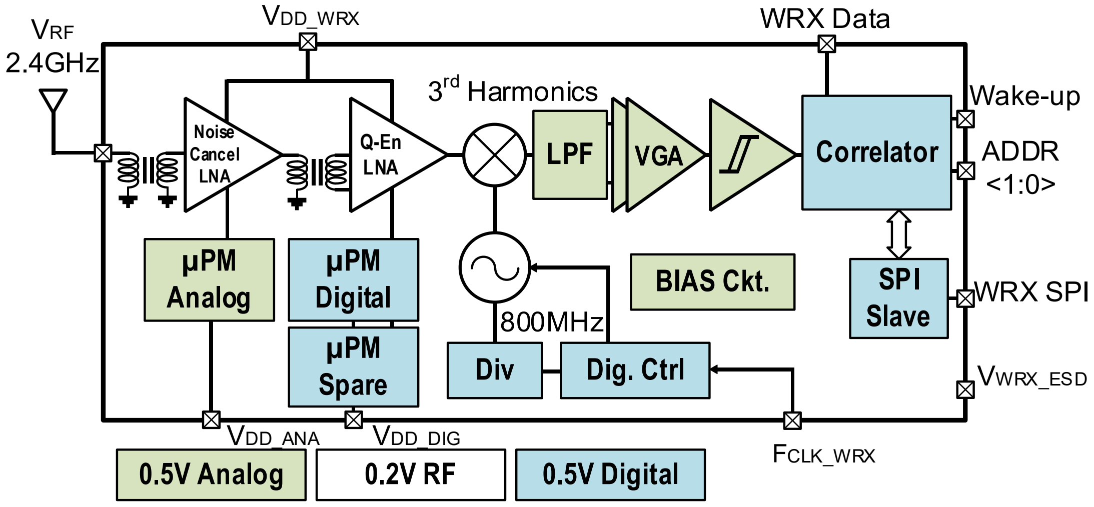
| | |
|---|---|
| • Demonstrate prototype WiFi wakeup receiver with < 1 mW active power<br>• Demonstrate prototype 5G wakeup receiver with < 500 µW active power | **2 wakeup receivers: WiFi and 5G (NB-IoT)** |
| • Demonstrate custom integration IC with <50 µW active power | **Node Controller IC** |
| • Prototype Connectivity Module and integrate with appliances | **Integrated prototyping** |
| • Lower MELs phantom energy by over 50%<br>• Lower MELs idle energy by over 20% | **Savings: simulated and measured** |

# Ultra-Low Power Wi-Fi Wakeup Receiver

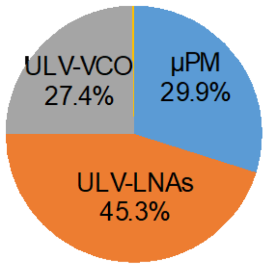
## Wakeup receiver for the WiFi 802.11ba draft standard for low power and low latency

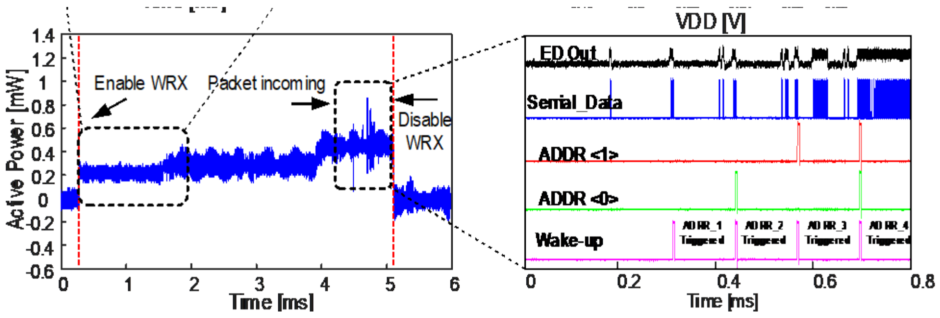
- Designed and fabricated a receiver for the draft WiFi wakeup standard 802.11ba
  - 2.4GHz WiFi band, for adoption into **all** future WiFi standards
- Chip design highlights
  - Operates from only 0.2V – lowest voltage receiver
  - Step-up transformers for noise cancelling and Q-enhanced - -91.5dBm sensitivity, -45dB SIR
  - 3rd harmonic mixing with 1/3 frequency RF oscillator
  - Two micro-power managers for full system integration
  - Active power of only 578μW

**WiFi Wakeup Receiver Chip Block Diagram**

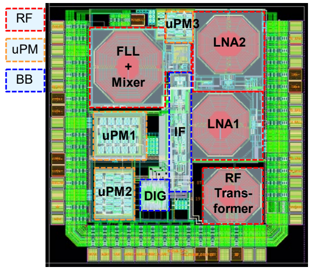



**Power Breakdown**
**Total: 578μW**




**Chip Photo**

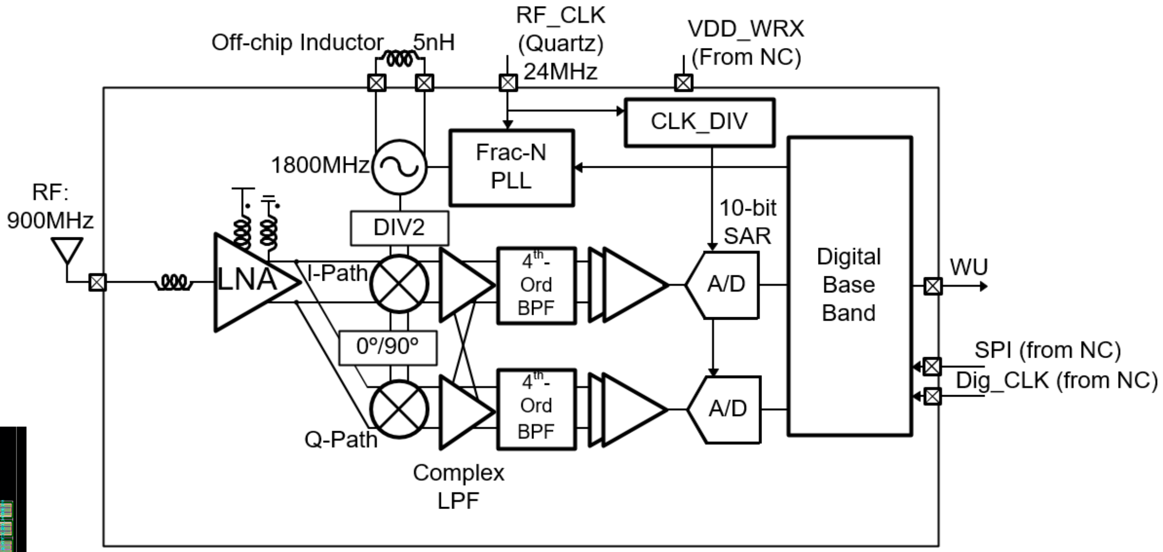


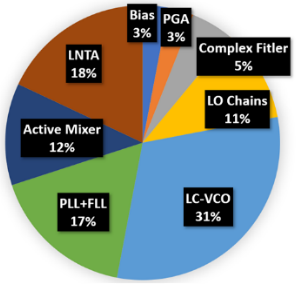
# Industry-First Cellular NB-IoT Compliant Wakeup Receiver

## Ultra-low power wakeup receiver targeting the worldwide cellular 4G/5G IoT standard, called NB-IoT

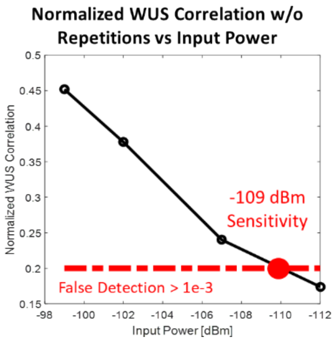
- Designed and fabricated a fully-compliant NB-IoT Wake Up Signal receiver (3GPP Release 15 NB-IoT Specification)
  - First published wakeup receiver for NB-IoT
  - Best in class power consumption (8-10x lower than other published NB-IoT receivers)
  - Wireless sensitivity compliant with NB-IoT requirement (-109dBm with no repetitions)
  - Active power of 2.1mW

**NB-IoT Wakeup Receiver Block Diagram**

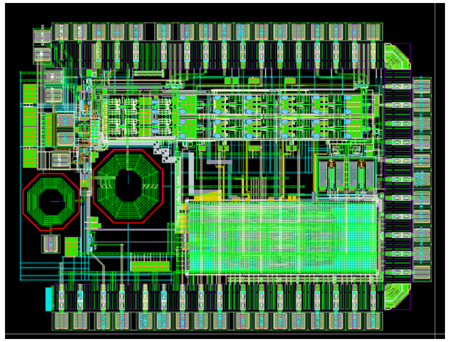


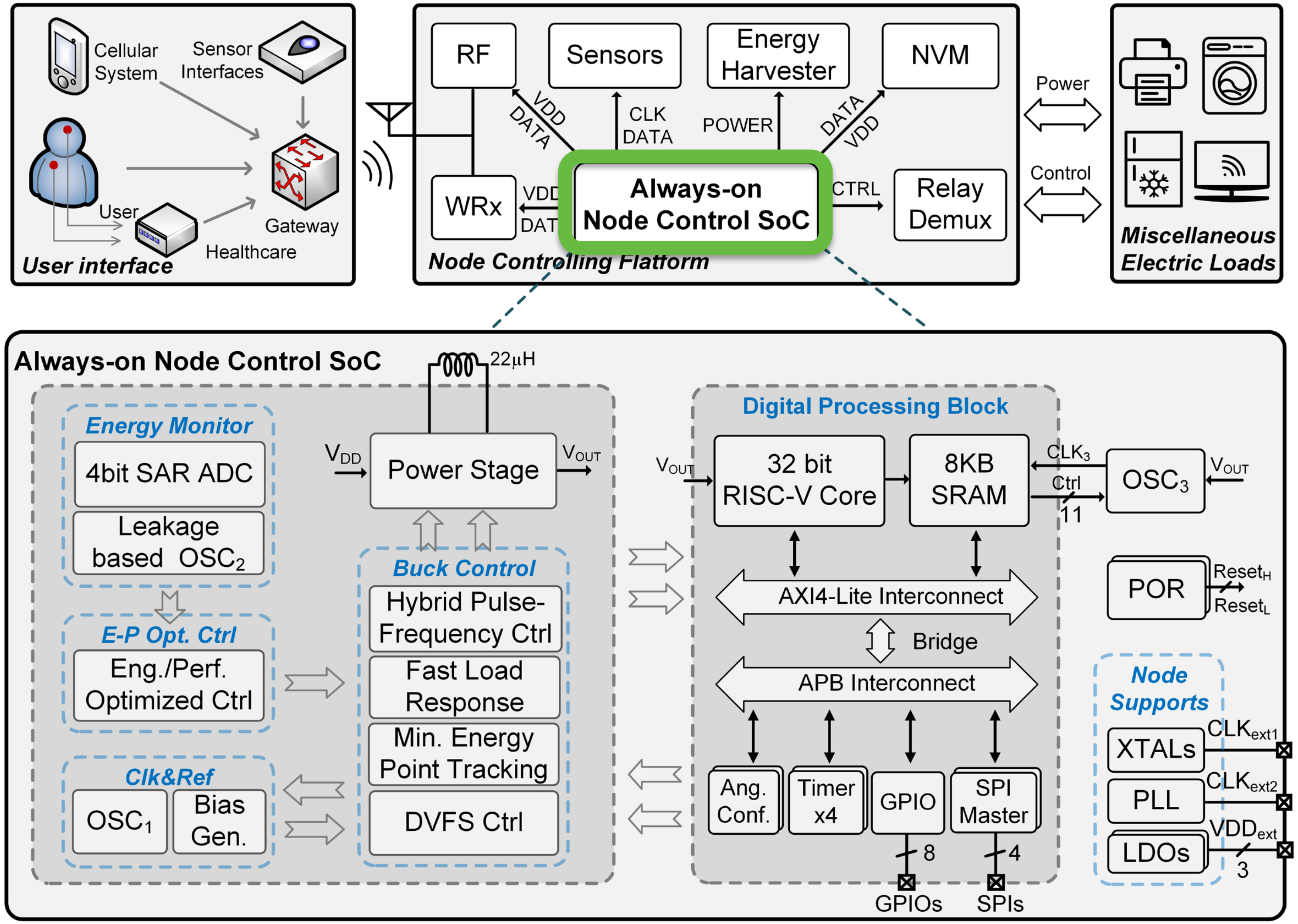

Total Power: 2.1mW




**Chip Photo**



# Node Controller IC Architecture



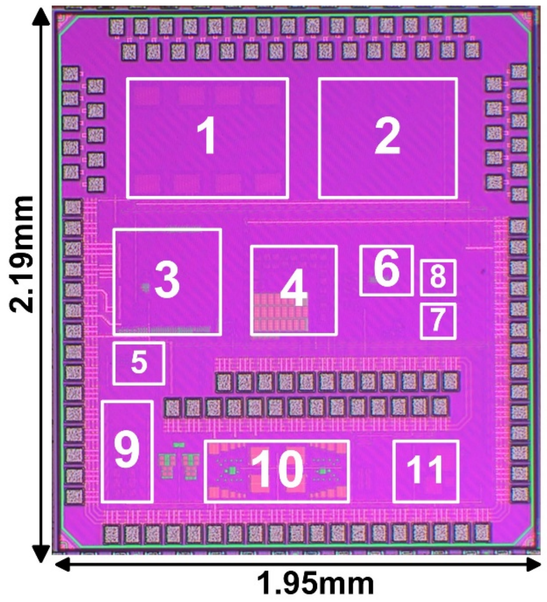

- System-on-Chip (SoC) handles always-on functions
- Processing and memory
  - RISC-V microcontroller
  - Clocks and control
- Supplies power
  - DC-DC conversion
  - Dynamic voltage and frequency scaling (DVFS)
- Ultra-low Power Operation
  - Targeted 50 μW active power
  - Enable always-on operation

# Node Controller Results

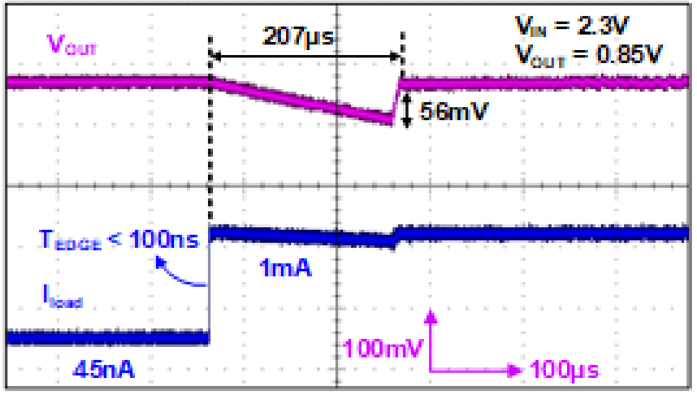
- Integrated DC-DC converter:
  - 0.8 nW, 93% efficient Buck Converter
  - 5,000,000x dynamic range with DVFS: 10s nA to mA
- Measured full chip power:
  - 500nW to 10 μW active power (run code)
  - 50 nW sleep power

✓ Node Controller chip is ready for integration

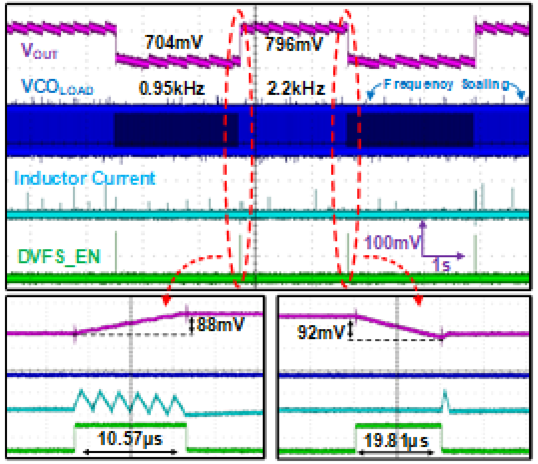
Chip Photo




| No. | Component |
|---|---|
| 1 | SRAM |
| 2 | RISCV |
| 3 | Buck Converter |
| 4 | VREF, IREF |
| 5 | Minimal Energy Point Tracker |
| 6 | ADC |
| 7 | Power on Rest |
| 8 | OSC |
| 9 | LDOs |
| 10 | XTAL |
| 11 | PLL |




Transient response of DC-DC




Measured DVFS operation

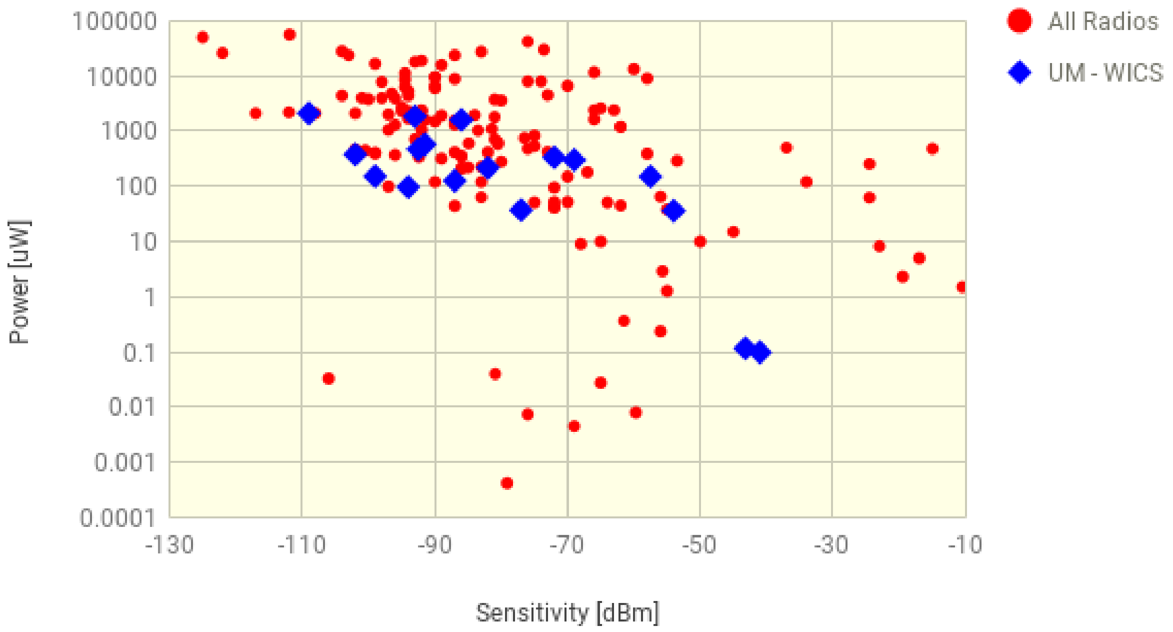
# Why Do Low Power Chips Matter for DoE?

- Leverage new chip technology to improve the performance of standards-based wireless connectivity modules.
  - Standard compliance is important for rapid industry adoption
  - WiFi / NB-IoT / ZigBee radios are high power (10s-100s of mW), leads to short battery lifetime
  - Ultra-low power wakeup receivers offer best of power and latency tradeoff

- Track record of ULP receiver design that pushes limits of power consumption, latency, data rate, and interference rejection
  - Plot on right shows power and sensitivity of ultra-low power receivers published by Prof. Wentzloff at U.Michigan (blue diamonds)
  - Custom controllers: always-on, flexible

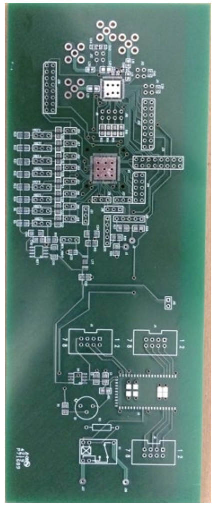
- **Benefits: Increased flexibility, true embedded intelligence, bigger savings**

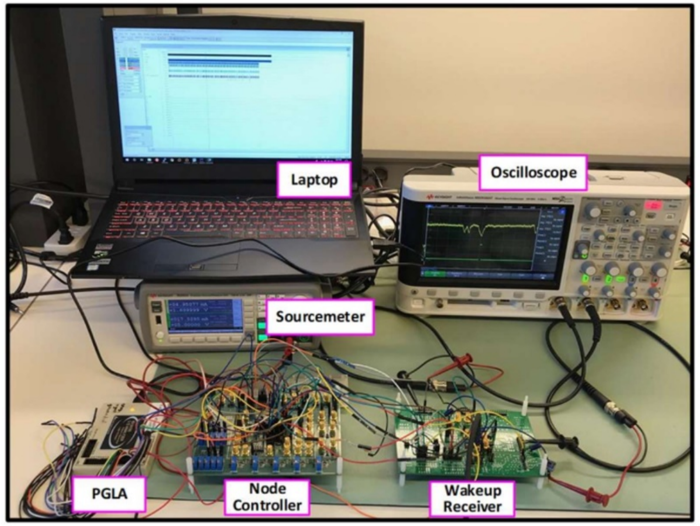
**ULP Radios Published 2005-Present**



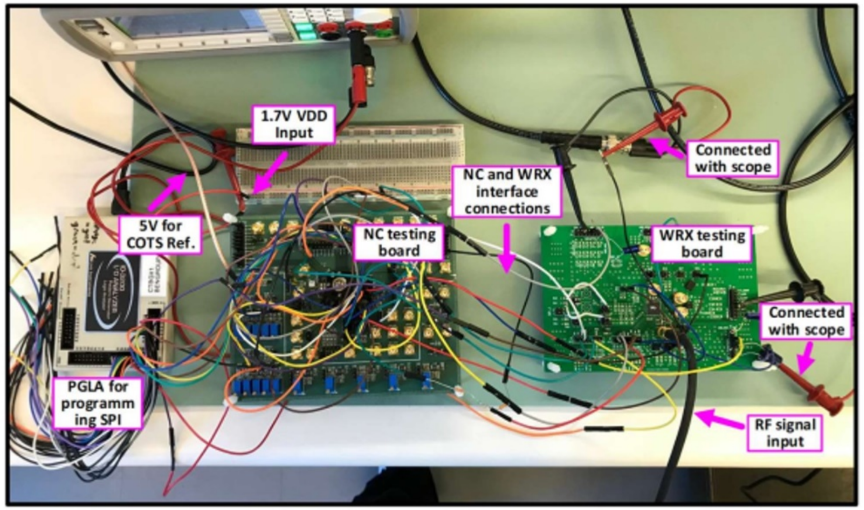
# Connectivity Module: Prototyping and Integration

- **Prototyping:**
  - Wakeup radio with node controller
  - Modules integrated with appliances
- **Connectivity module board: ready for integrating custom chips**
  - TODO: finalize chip testing and complete the integration

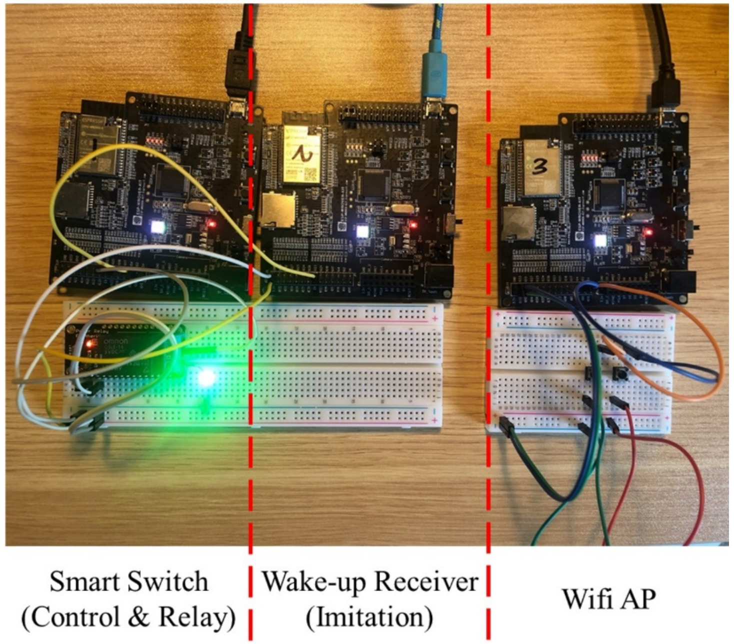





Measurement setup for the integration



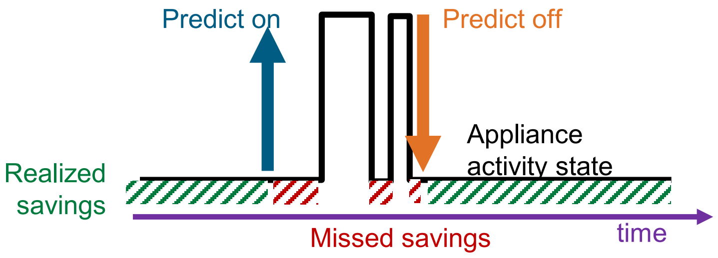

Detailed connections of the two IC boards



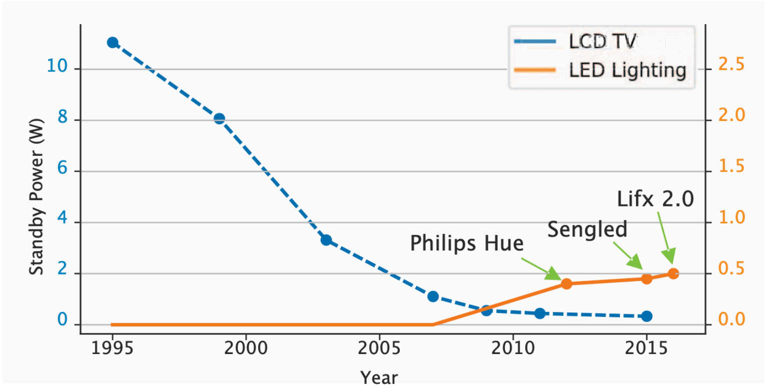
Smart Switch (Control & Relay) | Wake-up Receiver (Imitation) | Wifi AP

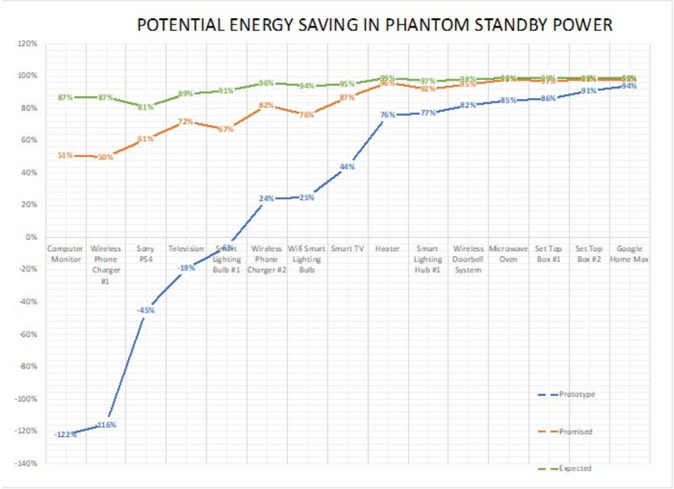
# Characterize the standby energy problem and estimate energy savings with ultra low power hardware

- Measure 32 MELs for standby power, active power, and startup time
- Using hardware and prediction algorithms developed in this project, **can reduce standby energy by 87% to 99%**
- Key finding: IoT MELs are worse standby than traditional MELs
  - Inspired AOI 5a ("The New Standby: Addressing Rising Energy Consumption from Always-on Connected Devices") in 2021 BTO CRADA Call



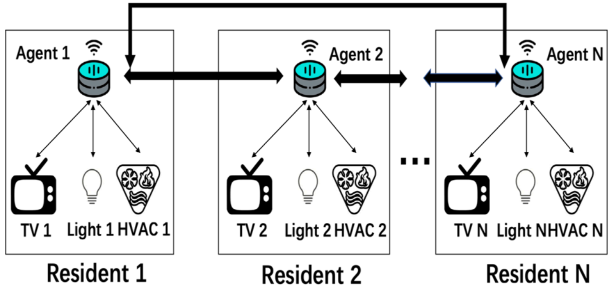

| Device Name | Off Mode (W) | Standby Mode (W) |
|---|---|---|
| Google Home Max | 4.72 | 4.72 |
| Amazon Echo Show | 0.17 | 7.36 |
| SmartThings Hub | 1.35 | 1.52 |
| Philips Hue Hub | 1.63 | 1.63 |
| Sengled Hub | 1.12 | 1.12 |
| Lutron Hub | 1.13 | 1.13 |
| Amazon Fire TV 4K | 2.62 | 2.62 |
| Google Chromecast | 1.69 | 1.69 |
| Sony PlayStation 4 | 0.17 | 6.31 |
| Xbox One S 1 TB | 0.28 | 24.50 |
| Geeni Smart Socket | 0.25 | 0.25 |
| Edimax Smart Socket | 1.43 | 1.43 |
| Geenie Smart Socket | 0.25 | 0.25 |
| Witenergy Smart Socket | 0.16 | 0.16 |
| Wit Smart Socket | 0.16 | 0.16 |
| Apple 60W Laptop Charger | 0.01 | 0.92 |
| Mophie 7.5W Wireless Charger | 0.12 | 0.12 |
| Samsung 9W Wireless Charger | 0.24 | 0.24 |
| Belkin 10W Wireless Charger | 0.52 | 0.52 |
| Philips Hue Bulb | 0.40 | 0.40 |
| Lifx Bulb | 0.48 | 0.48 |
| Sengled Bulb | 0.43 | 0.43 |
| Keurig K40 Coffee Maker | 3.26 | 4.12 |
| Gourmia GCMW4750 Coffee Maker | 0.95 | 0.95 |
| Sony X800E Smart TV | 0.42 | 23.80 |
| Bose Wave SoundTouch Speaker | 3.48 | 6.92 |
| Amazon Cloud Camera | 1.84 | 1.84 |
| Nest Hello Wireless Doorbell | 1.88 | 1.88 |
| Awair 2nd Edition Air Quality Sensor | 1.17 | 1.17 |
| Dell E2216H Monitor | 0.11 | 17.8 |
| Epson Pro G7400U Projector | 1.24 | 1.24 |
| Google AC1200 Wifi Router | 3.32 | 3.32 |
| Frigidaire 8000BTU Portable AC | 0.58 | 0.58 |

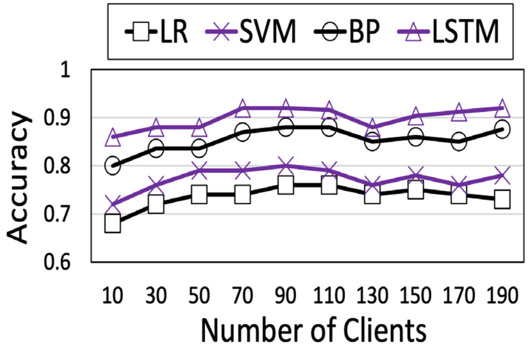


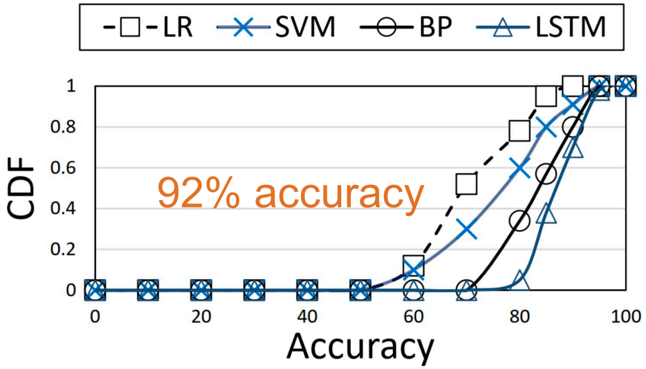



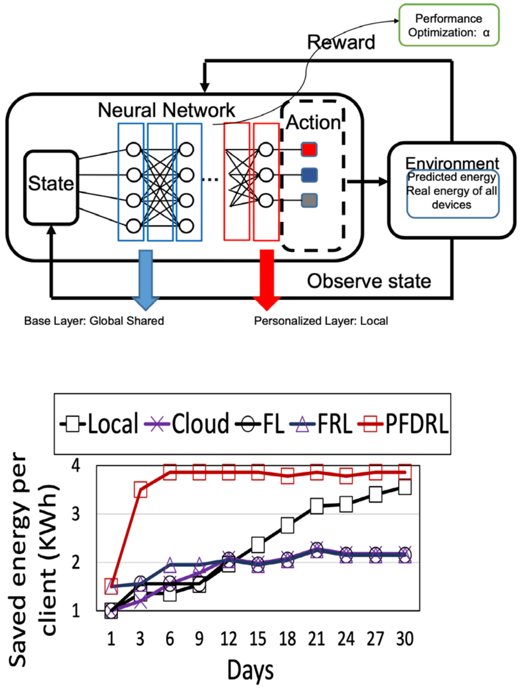
# MEL usage prediction with personalized reinforcement learning

- Predict MEL usage to improve user experience and maximize standby energy reduction
- Deep learning (LSTM) prediction 92% accuracy
- Accuracy improves with more data
  - Use distributed federated learning to allow multiple households to share data




- User privacy: users only share a few layers of their trained model
- Increased accuracy: train user-specific personalized layers in neural network model
  - Personalized model reaches 95% of maximum energy savings in only 3 days of learning

# Remaining Project Work

- **Complete Integrated Prototype of Connectivity Module:**
  - Integrate NB-IoT WRX and Node Controller with COTS components
  - Demonstrate prototype working with appliances
- **Revisit Impact:**
  - Demonstrate prototype WiFi wakeup receiver with < 1 mW active power - **DONE: 578µW (vs. 80,000µW for COTS)**
  - Demonstrate prototype 5G wakeup receiver with < 500 µW active power - **NEARLY DONE: 2.1mW (best in class by 10x)**
  - Demonstrate custom integration IC with <50 µW active power – **DONE: ~0.5 - 10µW active power and 50nW sleep (vs. 50 µW target and ~1,000 µW for COTS)**
  - Prototype Connectivity Module and integrate with appliances – **Showed appliance integration; showed chip integration; ready for module integration**
  - Lower MELs phantom energy by over 50% **Savings >87%: cut phantom energy to <1mW, with WoW and predicted turn-on**
  - Lower MELs idle energy by over 20% - **Showing >87% reduction in standby energy**

# Stakeholder Engagement

- **Multi-institutional Team with Complementary Strengths:**
  - U. Virginia: Low power IC control, MELs control
  - U. Michigan: Low power RF Ics
  - ORNL: MELs interface platforms

- **Broader Stakeholder Engagement:**
  - Learn about technology needs
  - Coordinate on interfacing requirements
  - Optimize for increased impact
  - Collaboration on future application of these advances

# Thank You


| | |
|---|---|
| Performing Organization(s): | University of Virginia, University of Michigan, ORNL |
| PI Name and Title: | Ben Calhoun, Professor, UVA |
| Email: | bcalhoun@virginia.edu |

# REFERENCE SLIDES

# Project Budget

**Project Budget**: $2,426,667 (excl. ORNL; $2,906,666 total)
**Variances**: No-cost extension for 12-months due to COVID-19. No other variances to date
**Cost to Date:** $2,242,800 of $2,426,667

| Budget History | | | | | |
|---|---|---|---|---|---|
| 1/1/18– FY 2020 (past) | | FY 2021 (current) | | FY 2022 – 12/31/21 (planned) | |
| DOE | Cost-share | DOE | Cost-share | DOE | Cost-share |
| $1,712,372 | $255,475 | $447,628 | $11,192 | N/A | N/A |

# Project Plan and Schedule

- Project dates: 1/1/18 to 12/31/21 – NCE extended schedule by 12 mos.
- Schedule  and Milestones: on schedule - see SOPO and PMP for details
- Milestones on track given NCE
- No future go/no-go decision points
- Current and future work: see SOPO and PMP for detail

| Project Schedule - RELEVANT HIGHLIGHTS | | |
|---|---|---|
| Project Start: 1/1/18 | | Completed Work |
| Projected End: 12/31/21 | | Active Task (in progress work) |
| | | Milestone/Deliverable (Originally Planned) |
| **SUMMARY: ON SCHEDULE** | | Milestone/Deliverable (Actual) |

| | CY2018 | | | | CY2019 | | | | CY2020 | | | | CY2021 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Task | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 |
| **Past Work** | | | | | | | | | | | | | | | | |
| BP1: see SOPO for details | | | | | | | | | | | | | | | | |
| BP2: see SOPO for details | | | | | | | | | | | | | | | | |
| Q1 Milestones: see SOPO for details | | | | | | | | | | | | | | | | |
| Q2 Milestones: see SOPO for details | | | | | | | | | | | | | | | | |
| Q3 Milestones: see SOPO for details | | | | | | | | | | | | | | | | |
| Q4 Milestones: see SOPO for details | | | | | | | | | | | | | | | | |
| **Current/Future Work** | | | | | | | | | | | | | | | | |
| Continuing work on BP3 milestones | | | | | | | | | | | | | | | | |