A Supporting Network for Crystal-Free Wireless Motes

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ABSTRACT

This paper details a demonstrated network architecture that passes data through an OpenWSN network linked to an LTE-M modem transmitting MQTT messages intended to support crystal-free device mesh networks. Crystal-free systems such as the Single-Chip micro Mote (SCμM) are designed for minimal power consumption and consist of a single piece of silicon needing only a power source and antenna. This design comes at a cost of reduced communication range and high clock jitter that must be periodically corrected from an outside source. Using the commercially available XIAO nRF52840 board and an LTE-M cellular modem connection, we constructed a proof-of-concept cellular-connected OpenWSN bridge network consisting of two types of mesh network node: a root node bridging LTE-M cellular network to OpenWSN, and OpenWSN-only repeater nodes based on the nRF52840. These nRF nodes also incorporated their own underwater acoustic environmental sensing to maximize their deployed utility. We envision this network as supporting clusters of thousands to millions of ultra low-power SCμM nodes, which also run the OpenWSN network stack but need a timing reference in the network and can currently only communicate over short distances.

CCS CONCEPTS

• **Computer systems organization** → **Embedded systems**; *Reliability*; • **Networks** → *Network protocol design.*

KEYWORDS

Crystal-free radio, low-power wireless, 6TiSCH, SCμM, nRF52840, LTE-M, Internet of Things (IoT), wireless sensor networks (WSN)

1 INTRODUCTION

Crystal-free systems omit external crystals for cost and power savings, and incur networking challenges as a result. SCμM has a transmit power of -8 dBm and a receiver sensitivity that results in a practical communication range of only a few meters under ideal conditions [1]. By replacing the crystal reference with an on-chip silicon oscillator, SCμM is based around clocks that face challenges in maintaining the timing required in wireless communication standards [2]. Despite the challenges, SCμM can communicate using the IEEE802.15.4 standard using the OpenWSN software stack [3]. Future work could see a large area blanketed with single-chip devices allowing for a dense mesh network. A supporting network constructed from crystal references commercially available SoCs could be used to provide a more accurate clock reference using packets provided by a OpenWSN network. The commercially available SoCs can also be used to connect discrete mesh networks and provide long-range communication using cellular connections. This paper presents a proof-of-concept for such an architecture, built with commercially available hardware. The network is envisioned as a tree structure consisting of:

"Trunk" Nodes: One or more bridges between low-power mesh network to a high-power backhaul, providing wide-area connectivity via LTE-M cellular modem.

"Branch" Nodes: Intermediate mesh nodes built using the XIAO nRF52840 microcontroller running the OpenWSN protocol stack. These nodes form a reliable, time-synchronized mesh network that can relay data from the less capable leaf nodes. This branch node proof of concept complements the existing OpenWSN work with the CC2538 SoC [4]. The nRF52840 branch nodes offer robust communication and sensing capabilities, crystal-free, single-chip wireless sensor systems are envisioned to serve as dense ultra-low-power collection of "leaf" nodes due to their inherently minimal power consumption, ultra-low manufacturing cost at scale, and extremely small form factor.

2 NETWORK IMPLEMENTATION

2.1 Hardware

Several commercial and custom PCBs were incorporated to form the various types of nodes in this project. These are pictured in Fig. 1.

Trunk Node (Sequans Monarch 2 GM02SP LTE-M Modem) The trunk node consists of a XIAO nRF52840 root node within the OpenWSN network acting as the central data aggregator. Its role is to receive information from the sensor node and forward it to a cloud storage solution using an cellular modem. The cellular protocol can vary according to the region of operation. The demonstrated hardware implements a LTE-M modem using the Sequans Monarch 2 GM02SP modem. For data processing tasks, it can also incorporate an always-on Teensy 4.0 processor. This node is designed for constant availability rather than power efficiency and requires a continuous power source for practical deployment.

Branch Node (Seeed Studio XIAO nRF52840 module) The branch node's function is to provide wireless mesh networking capability using the OpenWSN stack, allowing the crystal-free mote (leaf) nodes to transmit their data to the trunk node. The nRF52840 branch is used to increase communication distance and ensure accurate timekeeping in our tiered system. The demonstrated hardware also incorporates a Teensy 4.0 for sensor acquisition and data processing. To increase the utility of these nodes, our demonstrated project can perform environmental sensing in the form of underwater acoustic logging. For demonstration a microphone was connected to a Teensy Audio Adapter to acquire the 16-bit 44.1 kHz series. The data is stored on the node in flash memory for transmission over the wireless network and/or manual retrieval.

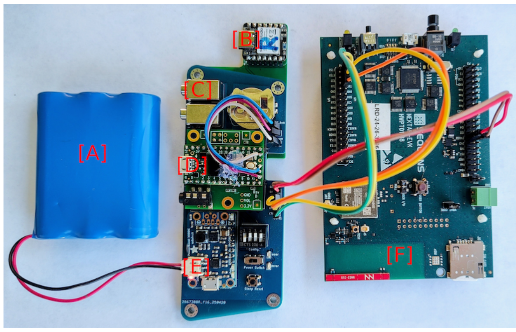

Figure 1: All hardware developed for project shown connected together to form OpenWSN/LTE-M bridge node: battery pack [A], XIAO nrf52840 [B], acoustic sensing interface [C] (hydrophone not pictured), Teensy 4.0 with a Teensy Audio Adaptor Board [D], power management board [E], and LTE-M evaluation module [F].

2.2 Software

The software effort focused on creating a functional OpenWSN mesh network on the XIAO platform and ensuring example sensor data it generated could reach the cloud via MQTT. This involved porting the existing OpenWSN firmware, originally for the nRF52840-DK, to the specific hardware layout of the Seeed Studio XIAO nRF52840. Key modifications were made within the board support package, specifically updating the UART and LED pin assignments in uart.c and leds.c to match the XIAO's pinout. Modifications were also made to the OpenWSN openserial driver to establish a communication channel for the Teensy 4.0 to pass processed acoustic data into the network.

The demonstrated root node uses a Teensy 4.0 to parse the XIAO's OpenWSN serial output. Data received at the root node is passed to the cellular modem using MQTT specific AT commands over a serial UART connection. A Google Cloud virtual machine is used to host a ThingsBoard.io [5] server that provides the MQTT broker, data storage, and a graphical UI.

The demonstration provides an ADC driver to use with an OpenWSN app "adcread". The app periodically samples an analog sensor using the an timer, making data available via a function called `adcread_get_value()`. The app can be used to capture a quick burst of samples. Then scheduling a non-blocking task to calculate results like the average, minimum, and maximum. The processed data, not the raw samples, is then made available for efficient network transmission.

3 PERFORMANCE AND POWER ANALYSIS

Power consumption analysis was completed using the JouleScope JS220. The device uses a voltage reference and current loop to generate statistical average current and power consumption. Where possible a node can transition between two states, an "active" state where data acquisition, process, and transmission take place and a second "sleep" state where the device is configured for a low power operation while otherwise idle. The average current consumption for both states is used to estimate battery life based on a duty-cycle between the two states. The network was demonstrated to be reliable in laboratory conditions for hours at a time, including live demos to lab group members.

3.1 Branch Node Performance

From lab measurements, we estimate a single 18650 (10,000 mAh) battery will power a node consisting of only a XIAO nRF52840 for 260.4 days.

Branch nodes include underwater acoustic sensing capability. If this logger is actively recording with a 1% duty cycle (14.4 minutes per day or 36 seconds every hour), the nRF52840 node battery life estimate is 93.0 days. More detailed analyses of duty cycle/lifetime tradeoffs can be found in our GitHub documentation [6].

3.2 Trunk Node Performance

We estimate the same battery will power our combination nRF52840 and LTE-M cellular bridge node for 1.7 days while using a Teensy 4.0 to process the data before transmitting via the cellular modem. Removing the Teensy would result in an estimated of 5.8 days of battery life.

4 CONCLUSION

This paper successfully demonstrated a tiered network architecture that bridges a low-power OpenWSN mesh with a long-range LTE-M cellular backhaul. This proof-of-concept, built with commercially available nRF52840 SoCs, establishes a robust framework for supporting future large-scale, ultra-low-power sensor deployments.[6]

Looking ahead, we envision this network being used to directly support crystal-free systems like SCμM by providing the stable, external timing reference they require to maintain network synchronization. It can also be used as a practical testbed to study the communication difficulties observed between today's single-chip motes and commercial nRF SoCs specifically. Furthermore, we intend to experiment with on-device signal processing of acoustic data. This will allow the computational load to be performed on a SCμM leaf node or an nRF52840 branch node with the goal of extracting useful signal information. This on-node precessing can reduce the network overhead associated with transmitting all preprocessed data.

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