Long-range & Self-powered IoT Devices for Agriculture & Aquaponics Based on Multi-hop Topology

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***Abstract*—This article presents the prototype design and testing of a long-range, self-powered IoT devices for use in precision agriculture and aquaponics. The devices are designed using the ultra-low power nRF52840 microcontroller with Bluetooth 5 support and ambient energy harvesting. A power of 942μW is harvested in an indoor environment. The devices are therefore suitable for both indoor and outdoor use, as natural sunlight will provide far more energy compared to artificial indoor lights. A line-of-sight range of up to 1.8km is achieved with the use of coded transmissions. However, the coverage area and range can be extended significantly by deploying the devices in multi-hop network topology. The custom multi-hop protocol provides energy efficient communication from any device in a wireless sensor network to a gateway while consuming an average of 267μW with a transmission interval of 5 minutes. The sensor data is transmitted to a gateway, which then forwards it to a local server or cloud service, where the data can be analyzed to optimize the production in agriculture and aquaponics.**

***Index Terms*—Wireless Sensor Networks, IoT, Wireless Embedded Systems, Energy Harvesting, Self-Powered IoT, Multi-Hop Topology, Agriculture, Aquaponics.**

I. Introduction

Internet of Things (IoT) enables the connectivity of smart devices over a network, and interaction among embedded devices. IoT has a wide range of applications such as smart homes, industrial surveillance and automation, healthcare services and agriculture [1]. A typical IoT system consists of several devices or nodes, where each node is embedded with a controller unit, transceiver, and sensors for a specific application. Actuators, which are triggered based on the sensor measurements, may also be implemented. The nodes can either be powered by cable, or by batteries, which typically need to be replaced or recharged. Recently, the use of energy harvesting on such nodes has become increasingly viable, which effectively allows for years of operation with no human intervention [2]. Normally, in a wireless IoT network, trade-offs must be made regarding energy consumption, bandwidth and transmission range as increased range typically leads to higher energy consumption. On the other hand, a higher bandwidth results in a shorter range [3].

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By deploying IoT devices in agriculture, critical parameters such as soil pH and nutrient content can be measured, logged and analyzed for optimizing the yield. These parameters can also be used in preventing over-fertilization or over-watering well in advance. Over-fertilization is known to harm the environment in multiple ways, such as excess fertilizer entering rivers or lakes, polluting the water and damaging the aquatic life [4]. Preventing over-watering is critical in areas with limited water supply. IoT nodes can also be used to implement precision farming techniques. Precision farming focuses on measuring soil properties and use the measurements to optimize soil sampling and management schemes [5]. In aquaponics, IoT devices can be deployed for optimizing the growth of both fish and plants by measuring and controlling values such as dissolved oxygen percentage and water temperature [6].

To optimize the critical parameters in agriculture and aquaponics, a fully self-powered, long-range IoT device with a custom ultra-low power (ULP) multi-hop protocol is designed and implemented. The article is further organised into four sections. Section II focuses on device design, measurement results are presented in section III and finally conclusion in section IV.

II. System Level Design

A visual representation of the data flow in the IoT system is presented in Fig. 1. Each of the modules is described in greater detail in the following section.

A. Sensor Node

The sensor nodes are designed with BMD-340, a module based on the nRF52840 microcontroller with on-board antenna and supporting circuit [7], [8]. The nRF52840 is developed by Nordic Semiconductor, and is designed for ultra-low power (ULP) wireless applications with Bluetooth 5 Long-range support. The nRF52840 preview development

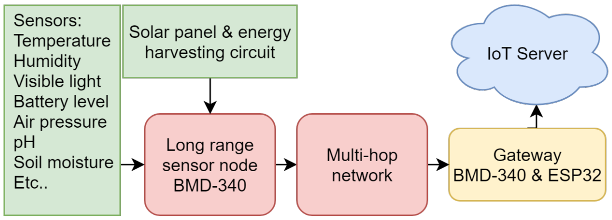

Fig. 1. IoT system overview

kit is used for verifying functionality. A PCB, shown in Fig. 2, is designed based on the tested prototype circuits. The PCB includes support for various on-board sensors for environmental values such as temperature, relative humidity, air pressure and visible light, which can be used to determine and predict crop health and growth. Battery voltage level is also measured in order to identify faults in the energy harvesting. The unused pins of the BMD-340, as well as the specified I^2C pins, are accessible through pin headers on the PCB to support sensors such as pH, nitrate levels and soil moisture. In order to further reduce the energy consumption of the nodes, Wake-Up Radio (WUR) may also be connected to the pin headers [9], [10]. The node is designed to function with power supply from both USB and energy harvesting, and can be programmed by using either J-TAG or USB.

The bq25570 IC from Texas Instruments is used for energy harvesting, battery charging and voltage conditioning [11]. The IC contains all necessary safety considrations for Lithium Ion (Li-Ion) batteries, such as programmable under and over voltage protection, as well as Maximum Power Point Tracking (MPPT) for optimizing the harvested energy from a solar panel. The configured output voltage from the bq25570 for the sensor node is $1.9V$, however, this can easily be modified to higher voltages should an external sensor requires it, as the BMD-340 and sensors can safely operate with supply voltages of up to $3.6V$. A Li-Ion battery with a capacity of $120mAh$ and a generic polycrystalline solar panel with a rated output of $0.36W$ is used for testing.

The sensor nodes are programmed to transmit at $8dBm$ power with a bitrate of $125kb/s$ in long-range mode. The actual bitrate is $1Mb/s$, however, 8 symbols are transmitted per data bit in a forward error correction (FEC) scheme. FEC enables the receiver to perform error detection and correction based on received symbols, allowing communication on what is usually considered lossy lings without increasing transmission power as the sensitivity of the receiving node is decreased. The energy consumption while transmitting is, however, increased, as the transmission requires more time.

B. Multi-Hop Topology

In order to extend the networks range further to allow for full coverage of large fields, a custom, ultra low power (ULP) multi-hop protocol is developed and implemented. With this protocol, a network of nodes are able to route messages towards a dedicated gateway, where the closest gateway will be chosen after the network has adapted to its topology.

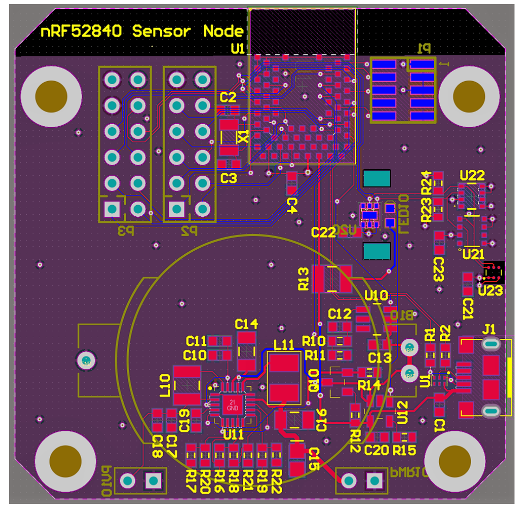

Fig. 2. Node PCB design

Fig. 3 shows the basic concept of multi-hop protocol. At the startup of each node, the radio is initialized with the necessary registry modifications. A counter is then initialized, and the node enters sleep state for a given interval of time. After this interval, the node wakes up, increments the counter and checks the value of the counter. If the counter is below a programmed value, 10 in the example shown in Fig. 3, the node broadcasts a wake ping message, and waits for replies from nodes that want to transmit data. If no neighboring node wants to transmit data, the node returns to sleep. If a neighboring node transmits data, the node forwards this data to the first node that transmits a wake ping message with a number of hops to gateway lower than itself. After an acknowledgement message (ACK) is received from the next-hop node, the relaying process is repeated. The node also updates its hops to gateway equal to that of the next hop node plus one before going back to sleep. Once the counter reaches 10, the node will attempt transmission of its own sensor data in the same manner as when relaying data. A random back-off is utilized as data transmissions are initiated by a broadcast message. When receiving this broadcast, all nodes which have data to transmit waits for a short random interval before performing a carrier sensing to check if the medium is idle or not. The node that drew the shortest interval will be able to transmit its data, while other nodes adjacent to the relaying node waits for the next wake-ping.

The gateway(s) broadcast wake ping messages with hops to gateway set to zero. Adjacent nodes identify this as a gateway node, and set their hops to gateway to one. Routes to the gateway will then propagate throughout the network. As any node that broadcasts hops to gateway = 0 is identified as a gateway, several gateways can be placed in the same

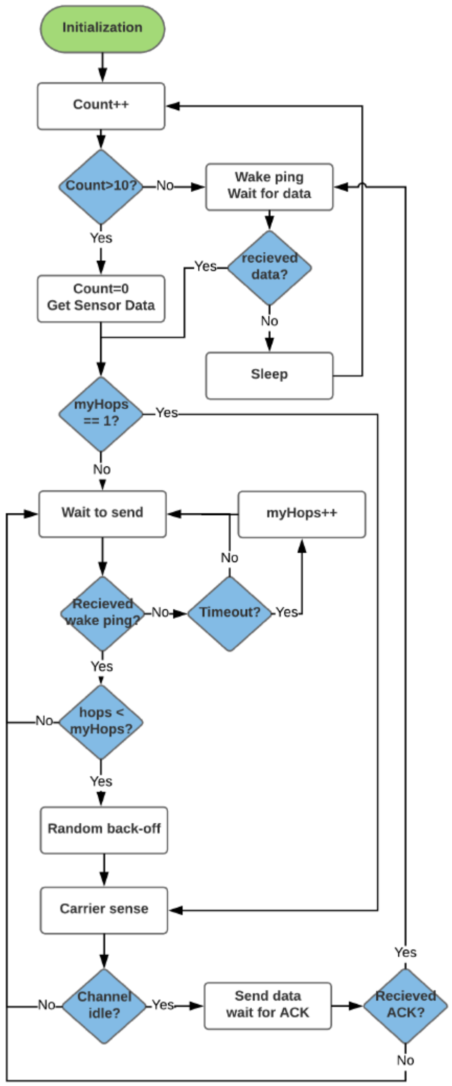

Fig. 3. Multi-hop protocol flowchart

network, and surrounding nodes will simply transmit towards the nearest one in terms of hops, and the gateways will publish the data via MQTT over Wi-Fi.

The payload has been optimized for the custom protocol in order to reduce overhead, which in turn reduces the energy consumption. Fig. 4 shows the payload of the data message. The payload is up to 22 bytes, which contains message type, destination ID, my ID, source ID, hops traveled, packet number and 8-15 bytes of sensor data.

	Payload data message						
Content	Message type	DestinationID	My ID	SourceID	Hops traveled	Packet nr.	Sensor data
Number of bytes	1	1	1	1	1	2	8 - 15
Range	0 - 2	0 - 255	0 - 255	0 - 255	0 - 255	0 - 65535	Data

Fig. 4. Payload of data message

Fig. 5 shows the payload of wake ping and ACK messages. The wake ping messages have a total payload of 3 bytes, while ACK has 4 bytes.

	Payload wake ping		
Content	Message type	My ID	Hops to gateway
Number of bytes	1	1	1
Range	0 - 2	0 - 255	0 - 255

	Payload ACK message		
Content	Message type	Your ID	Packet nr.
Number of bytes	1	1	2
Range	0 - 2	0 - 255	0 - 65535

Fig. 5. Payload of Wake Ping and ACK messages

C. Gateway

The gateway is designed and tested based on nRF52840 and ESP32 microcontroller with integrated Wi-Fi. The nRF52840 receives data from the sensor nodes and sends the data to ESP32 via a wired UART connection. The ESP32 then forwards the data by using the lightweight MQTT protocol via a Wi-Fi connection to an MQTT server, which may be on a local network or in the cloud.

III. Measurement Results and Discussion

A. Energy Harvesting

The energy harvesting circuit was tested with a $0.36W$ solar panel and a $120mAh$ Li-Ion battery in an indoor office environment over a period of 60 hours. The resulting average harvested energy during the period was $942\mu W$.

B. Range

The range of the sensor nodes was tested by the use of a drone at $40m$ height above ground level. The node was configured with the aforementioned $125kb/s$ coded transmission at $8dBm$ power, with a maximum obtained range of $1.8km$ in line of sight.

C. Energy Consumption

The energy consumption was obtained by measuring the voltage over a 5Ω resistor in series with the node usung an oscilloscope. Based on the measurements, the current and power consumption was calculated. The measurements are shown in detail in various segments with their respective periods and power consumption. A transmission interval of 5 minutes, and 3 relays per transmission, are assumed in the energy consumption calculations. The measured power in sleeping mode is $6.94\mu W$.

1) Wake ping message: Fig. 6 shows a single wake ping with a total period of $1.93ms$. Table I outlines the power consumption of the different stages of a single wake ping. The measurement is divided in three parts: Wake ping transmission, wait for data and a gap for switching between transmitting and receiving.

2) Data transmission: Fig. 7 shows one data transmission with a total period of $32.2ms$. Table II outlines the power consumption of the different stages of the transmission.

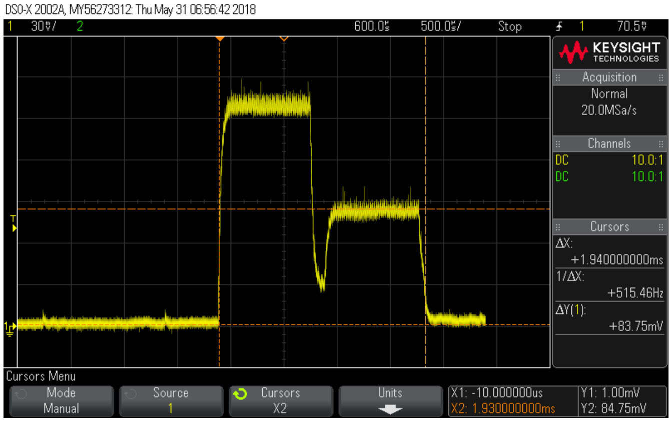

Fig. 6. Power measurement during wake ping

TABLE I
BREAKDOWN OF ENERGY CONSUMPTION FROM AWAKE PING MESSAGE

State	Period	Current	Power
MCU on	$220\mu s$	$6.9mA$	$13.1mW$
Wake ping transmit	$860\mu s$	$31.8mA$	$60.3mW$
Wait for data	$850\mu s$	$16.8mA$	$31.8mW$

3) Resulting average consumption: With the assumption of a 5 minute transmission interval, and 3 relays per transmission, the optimal average consumption of $267\mu W$ was measured at a $0.6s$ wake ping interval. This effectively means that the data will propagate from source to a gateway in a matter of seconds, as the maximum *wait to send* period is $0.6s$ for each hop.

With energy harvesting levels 3.5 times higher than the consumption in an indoor office environment with little natural light, the nodes can safely be used in agriculture and aquaponics. The transmission interval and size of solar panel can be adjusted to optimize the consumption based on harvested levels.

D. Multi-Hop Network Behaviour

The multi-hop protocol proved to be highly dynamic. Any node can be moved around in, added to or removed from the network at any time inside the cluster. As long as the nodes are with in the range of each other, they adapt to any change in the topology. Therefore, the proposed design is not only viable for stationary applications such as monitoring of large agriculture field or aquaponics, but also for tracking moving machinery or animals.

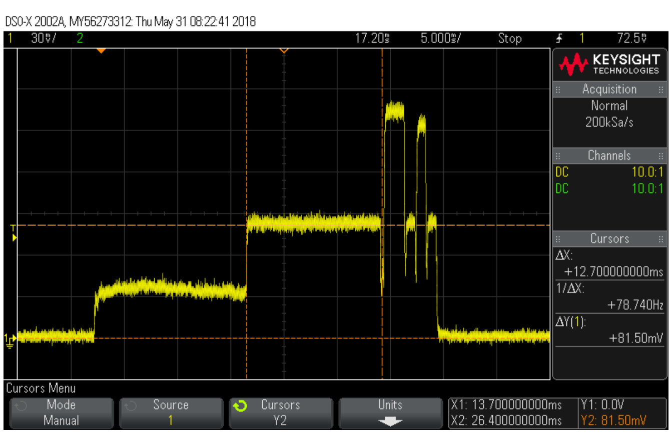

Fig. 7. Power measurement during data transmission

TABLE II
BREAKDOWN OF ENERGY CONSUMPTION FROM A FULL TRANSMISSION

State	Period	Current	Power
MCU on	$16.3ms$	$7mA$	$13.3mW$
Wait to send	$12.7ms$	$16.5mA$	$31.3mW$
Carrier sense	$128\mu s$	$16.7mA$	$31.7mW$
Random backoff	$80\mu s$	$16.7mA$	$31.7mW$
Transmit data	$1.9ms$	$32.6mA$	$61.9mW$
Wait for ACK	$900\mu s$	$16.5mA$	$31.3mW$
Wake ping transmit	$860\mu s$	$31.8mA$	$60.3mW$
Wait for data	$850\mu s$	$16.8mA$	$31.8mW$

IV. CONCLUSION

IoT devices for agriculture and aquaponics have been designed and tested based on the nRF52840 with a multi-hop protocol and energy harvesting. The nodes do not require any maintenance during the lifetime of the components, and harvest energy several times more than the consumption. The nodes are embedded with environmental sensors, with the option of adding external sensors for soil measurement, animal tracking and for measuring several parameters in aquaponics. The multi-hop protocol is highly efficient with ranges of up to $1.8km$ per hop, and a maximum hop-by-hop delay of $0.6s$ assuming successful transmissions. Additionally, due to its dynamic nature, nodes can be moved, added or removed from the topology without any issues, as the topology will quickly adapt to any changes.

A gateway is designed to forward data from the sensor network to a local network server or the Internet by using the lightweight MQTT protocol using Wi-Fi, where the sensor data can be analyzed to optimize agriculture and aquaponics.

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