Design and Implementation of an Ultra-Low Power Wake-up Radio for Wireless IoT Devices

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***Abstract*—In this paper, we present the design and prototype implementation of an ultra-low power wake-up radio for wireless IoT devices. The prototyped wake-up radio consumes only 580nA from 3V power supply, covers distance range of up to 55 meters and achieves a sensitivity of -49.5dBm. This wakeup radio module can easily be integrated into wireless IoT devices and thereby reducing the overall power consumption of the battery powered and energy harvesting based devices. The prolonged life time of the devices can reduce the overall costs when deployed in large scale.**

Keywords—Ultra-low power wireless IoT devices, wake-up radio, and wireless embedded systems.

I. INTRODUCTION

Wireless internet of things (IoT) is transforming day to day life in many aspects and it is expected that there will be about 50 billion IoT connected devices by 2020 [1]. Most of these devices are either battery (both rechargeable and non-rechargeable) powered or based on energy harvesting from ambient sources [1]. Due to increased demand for wireless IoT devices, better solutions are required to save battery power to prolong the life time of these devices. Most of the wireless IoT nodes today utilize duty cycling. Duty cycling nodes provide a state of idle or parked but are on to sense if the master node wants to exchange data with it. This causes idle listening and overhearing in the network. If we consider a Bluetooth piconet, the slave or peripheral node will send out an announcement to connect with a master node [2]. The slave or peripheral node will "wake up" each cycle to check if the master node wants to talk. The point of this is to minimize the idle listening of the sensor nodes, but this does not eliminate idle listening.

To eliminate this problem, implementation of an on-demand wake-up radio is a viable solution as shown in Figure 1.

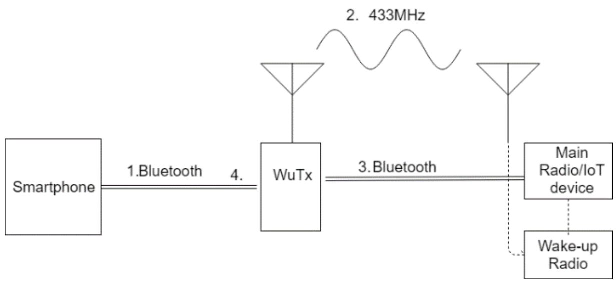

Fig. 1. Design of Wakeup radio.

The implementation of wake-up radios will provide much less power consumption to the network nodes as well as reduced response time. A wake-up radio provides a wake-up call to a sensor only when the user asks for it (on-demand). In this way the sensor only transmits data when it is required.

There are reported wakeup radio solutions based on simulation and hardware. Simulation based ones are not really of much use when it comes to practical implementation. Reported hardware-based ones are not very cost effective and not ultra-low powered [3-5]. These also do not achieve very good sensitivity that is needed for variety of wireless IoT technologies [3-5]. This article presents an ultra-low power wake-up radio based on hardware and it can easily be integrated into wireless IoT devices.

II. DESIGN OF ULTRA-LOW POWER WAKE-UP RADIO

The Wake-up radio consists of 4 major parts as shown in Figure 2. It includes a matching filter, an envelope detector, a comparator and a preamble detector.

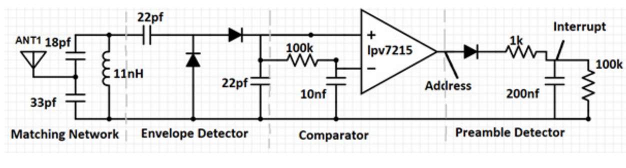

Fig. 2. Design of Wakeup radio.

The Matching filter provides appropriate matching to the received signal to preserve the received power and is tuned to a 50Ω antenna. The filter consists of two capacitors and one inductor. The filter is designed to have a narrow bandwidth in order to minimize the number of false wake ups. Since the impedance of the peak detector will be higher than the impedance of the antenna (50Ω), a voltage gain is included after the matching filter. Matching network is verified by using a network analyzer and measurements of S22 parameter as shown in Figure 3.

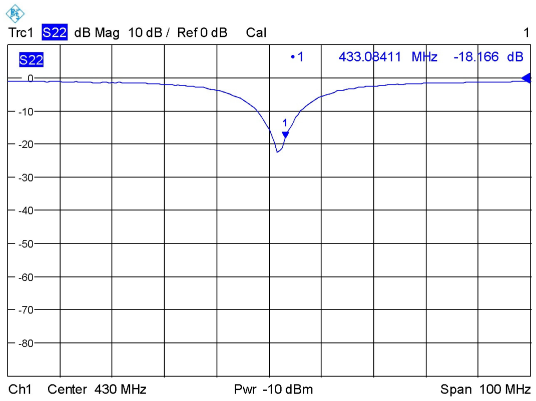

Fig. 3. Reflection measurement (Screenshot from network analyzer).

The percentage of the reflection of the received signal is:

$$r = 10^{-\frac{18.166}{20}} = 0.123 \quad (1)$$

$$\frac{P_r}{P_t} = \frac{\frac{(V^-)^2}{50}}{\frac{(V^+)^2}{50}} = \left(\frac{V^-}{V^+}\right)^2 = (r)^2 = 0.123^2 = 0.015 \quad (2)$$

With a reflection coefficient of -18.16dB, the matching filter will only reflect 1.5% of the received signal.

The envelope detector demodulates the envelope transmitted from the transmitter. The diode, HSMS-2850-TR1G is used to demodulate low power RF signal. Diodes with less leakage is essential in the design as it will reduce the voltage to the comparator.

The comparator detects the pulses from the envelope detector and generates pulses that can be interpreted by the microcontroller unit (MCU). The comparator used in this design is LPV7215 with a power consumption of 580nA and an offset voltage of +/- 0.3mV.

The preamble detector sends an interrupt signal to the MCU, telling it to wake up and start decoding the address. This is done to minimize false wake-ups from smaller and shorter signals. The achieved sensitivity of this design is -49.5dBm. This was measured by using an rf-generator and a signal generator as a modulator to mimic the signal transmitted from the transmitter. The sensitivity was found by measuring the lowest power level the wake-up radio was able to demodulate.

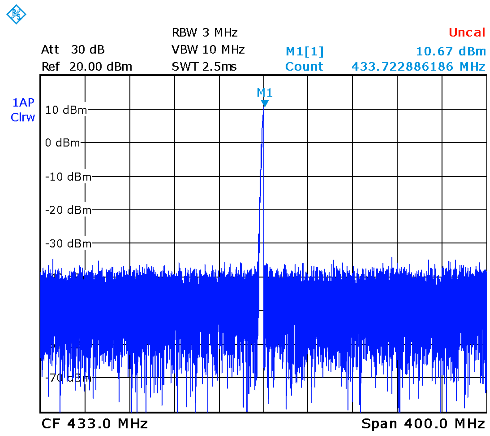

Fig. 4. Transmit power measurement (Screenshot from spectrum analyzer).

Figure 4 shows the transmission power and frequency from the transmitter. It was measured a signal strength of +10dBm at the transmitter.

With these results, theoretically a distance of 55 meters is achieved assuming 0dB antenna gain and no fading. TX = 10dBm, $RX_{sensitivity}$ = -49.5dBm, Ant_{gain} = 0dB.

We can calculate theoretical distance as follows:

$$\text{Distance} = 10^{TX - RX_{sensitivity} + (2*Ant_{gain})} * \frac{\lambda}{4*pi} = 55m \quad (3)$$

The reflection coefficient of the antennas is measured to be -2.6dB as shown in Figure 5. This will cause a reflection of 55% and reducing the signal drastically at both ends.

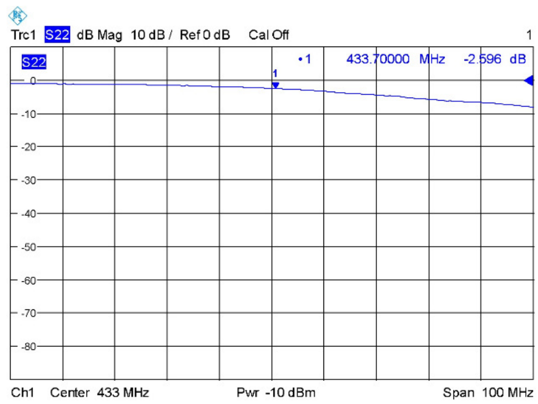

Fig. 5. Reflection measurement of antennas (Screenshot from network analyzer).

The gain was measured between two of these antennas with 10cm between them. This distance gives a fading of 5.17dB.

$$20 * \log\left(\frac{4*pi}{\lambda} * d\right) = 5.17\ dB \quad (4)$$

The measured signal strength between antennas was -15dBm as shown in Figure 6.

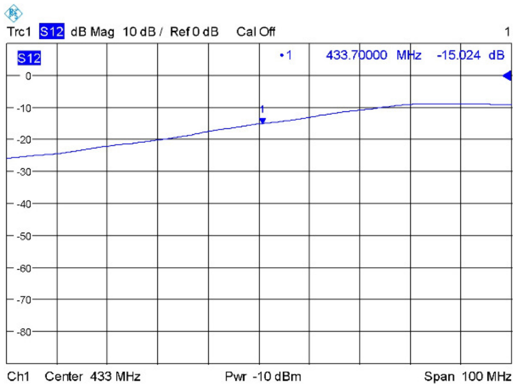

Fig. 6. Measured signal strength between two antennas.

The gain of these antennas at 433MHz will be:

$$\left(\frac{-15+5}{2}\right) = -5dBi \tag{5}$$

With the measured antenna gain of -5dBi, the theoretical distance that can be achieved is 17 meters.

TX = 10dBm, $RX_{sensitivity}$ = -49.5dBm, Ant_{gain} = -5dBi. The theoretical distance can be calculated as below:

$$\text{Distance} = 10^{TX-RX_{sensitivity}+(2*Ant_{gain})} * \frac{\lambda}{4*pi} = 17.43m \tag{6}$$

III. IMPLEMENTATION OF ULTRA-LOW POWER WAKE-UP RADIO

The complete system consists of three parts, a smartphone, a wake-up radio transmitter (WuTx) shown in Figure 7 and the sensor with the attached wake-up radio receiver (WuRx) shown in Figure 8. The smartphone is connected to WuTx through Bluetooth. Smartphone is used for sending the address to transmit and to receive the sensor data from WuTx. When the smartphone transmits the address, the WuTx will then generate a RF-representation of the address using OOK/ASK modulation. When the WuRx receive the address, it will demodulate the signal and sample the address in a bit-by-bit manner [6].

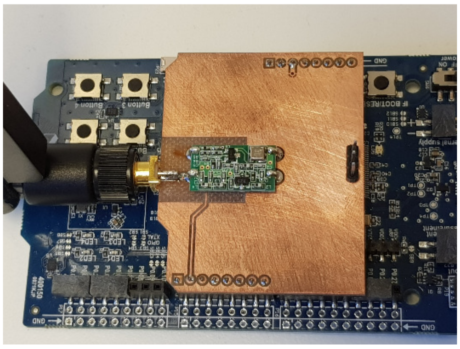

Fig. 7. Wakeup radio transmitter (WuTx).

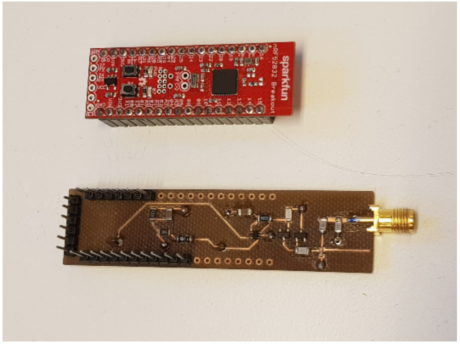

Fig. 8. Main radio (top) and wakeup radio receiver (bottom).

If the address matches with the address of the main radio then it will wake-up, enable a connection with the WuTx through Bluetooth and transmit the sensor data. The WuTx will then relay the sensor data to the smartphone for visual representation. Smartphone acts as a master towards the WuTx where as WuTx act as a master towards the WuRx.

Both the main radio and the WuTx use nRF52832 [7]. The WuTx uses also an external RF-transmitter to transmit the address over 433MHz. The smartphone uses the Nordic UART application for android [8]. The sensor is an integrated temperature sensor in the nRF52843.

IV. MEASUREMENT RESULTS

For the prototyped wake-up radio a theoretical distance of 55 meters and a current consumption of only 880nA was achieved with 0dB antenna gain. Antenna gain was measured to be -5dBi and this translates to a theoretical distance of 17 meters. Measured distance was 16 meters and very well matches with theoretical results.

The performance of the recently reported hardware-based wake-up radios for similar applications are shown in table 1. It can be clearly observed that proposed wake-up radio consumes only 1.7µW and achieves sensitivity of -49.5dBm.

TABLE I. PERFORMANCE COMPARISON

Ref.	Frequency (MHz)	Power Consumption (µW)	Sensitivity (dBm)
[3]	868	820	-51
[4]	869	13	-4.37
[5]	2400	1	-19
This work	433	1.7	-49.5

From the table, it can be observed that design reported in [5] consumes only 1µW but achieves sensitivity of only -19 dBm whereas this prototype achieves sensitivity of -49.5dBm. The various frequencies are included instead of distance. If we use the same transmission power and antennas, higher frequencies will have shorter distances than lower frequencies.

V. CONCLUSION

An ultra-low power wakeup radio enabled wireless IoT node was prototyped and tested. It achieves a sensitivity of -49.5 dBm and a distance of 55 meters with current consumption of only 580nA from a 3V power supply. It fits best for battery powered and energy harvesting based wireless IoT devices.

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