Ultra-Low Power Wakeup Radios In Medical Implant Communications

By P.D. Bradley and Reghu Rajan

Medical devices are increasingly incorporating wireless functionality to support new monitoring, diagnostic, and therapeutic applications that are improving patient care and lowering healthcare costs. Implantable medical devices often utilize wireless communication systems to support home-based patient remote monitoring, operating room device programming, and other features. These wireless devices have significant power constraints, due to their small size and the requirement to operate off small batteries for long periods of time. This paper will examine some of the requirements of such wireless implantable medical devices, the need for low power wakeup radios to support them, and a comparison of candidate technology.

Low Power Communication Requirements

Sensors or control nodes for wireless medical implants often have size constraints that dictate operation from a coin cell, small battery, or possibly even an energy harvesting source. Very low power sensors save power by operating predominately in a sleep mode, waking up from this sleep state only when measurement or data transmission is required. The requirements on the responsiveness of these sensors to human or machine interaction varies. In general, the initiation of communication to low power sensors may be grouped into two broad categories:

Regular Timed Events: Low power sensor nodes generally report infrequently in order to save power. The longevity of the battery may often be limited by system leakage current if the communication is very infrequent.

Asynchronous Events: In asynchronous events, the node does not know in advance when a communication interaction will occur. Many systems require a communication session that is initiated by a user or machine and requires fast attention. Such situations may occur when a user comes in close proximity to the sensor.

Ideally, humans prefer <0.7 second response for negligible perception of delay, and responses longer than a few seconds may become uncomfortable and even annoying for the user in many applications. These applications benefit greatly from a low power wakeup radio.

An Example Application Using Low Power Wakeup Radios

Medical implant communications often consist of once daily or weekly reporting of device status and operation to a clinician. For example, such communications may include battery status or ECG waveforms for an implantable cardioverter defibrillator (ICD). However, during device implantation or follow-up in a clinician's office much faster communication response is required, with device wakeup requirements less than 1 second desired.

A particularly important case occurs for some types of implantable neurostimulators. Chronic back pain may be managed by neurostimulation of the spinal cord using an implanted device, as shown in **Error! Reference source not found.**. This is a treatment for chronic neuropathic pain, where the electrical stimulation replaces the pain with a buzzing or tingling feeling in the area of the pain. Current products suffer the major problem that as the patient changes posture, the spinal cord moves relative to the electrode causing the level of stimulation of the nerves to change. This variability causes many patients severe discomfort, resulting in patients needing to continuously manually adjust the level of stimulation. Such patients require rapid initiation of communications with wakeup requirements less than 1 second.

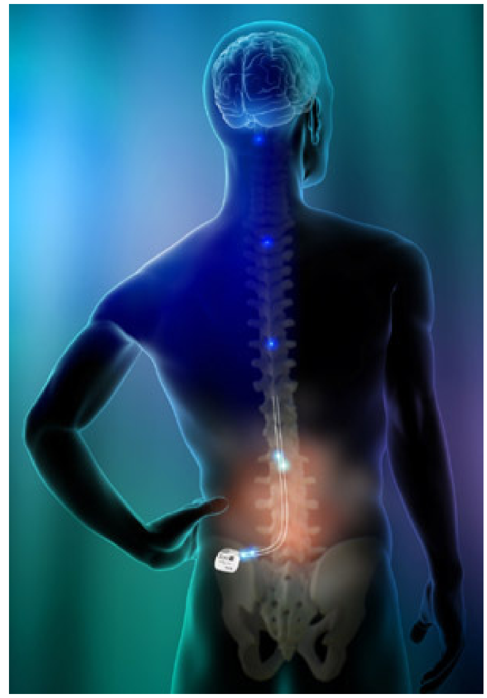

Figure 1: ***Implantable neurostimulator***

The implant does not know in advance when a communication request will occur, so a radio that is listening for a communication request is required. Such a radio must have a very low average current while still satisfying range (sensitivity) and interferer handling (filtering and reliability) requirements.

Microsemi/Zarlink has developed and implemented medical implant communication technology that includes dedicated wakeup radios in the ZL70102 family of products [1,2]. These transceivers incorporate a wakeup receiver that allows the ICs to operate in an extremely low current (290 nA average) sleep state. Communication between implanted and base station transceivers is then initiated using a specially coded wakeup signal from the 2.45-GHz base transmitter, as shown in Figure 2. Alternative wake-up mechanisms using 400-MHz or direct wake-up by the implanted medical device are also supported.

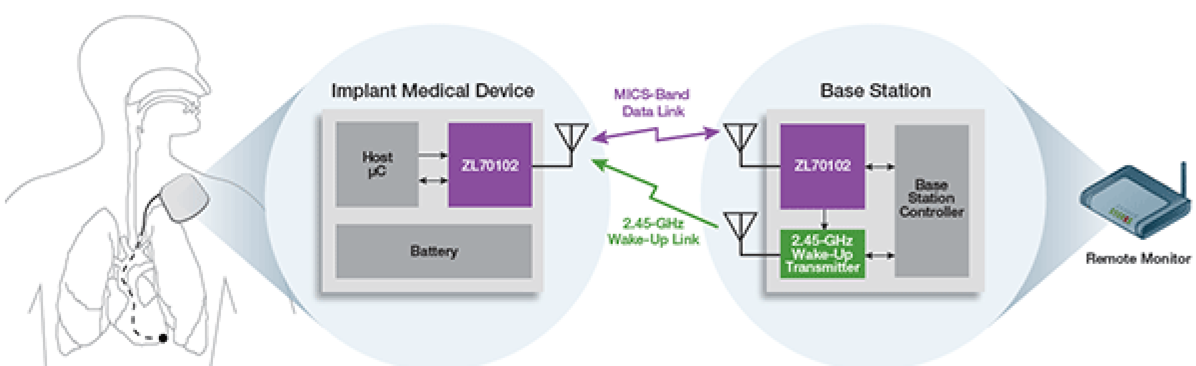

Figure 2: *Communication between implanted and base station ZL70102 transceivers is initiated using a specially coded wake-up signal from the 2.45-GHz base transmitter.*

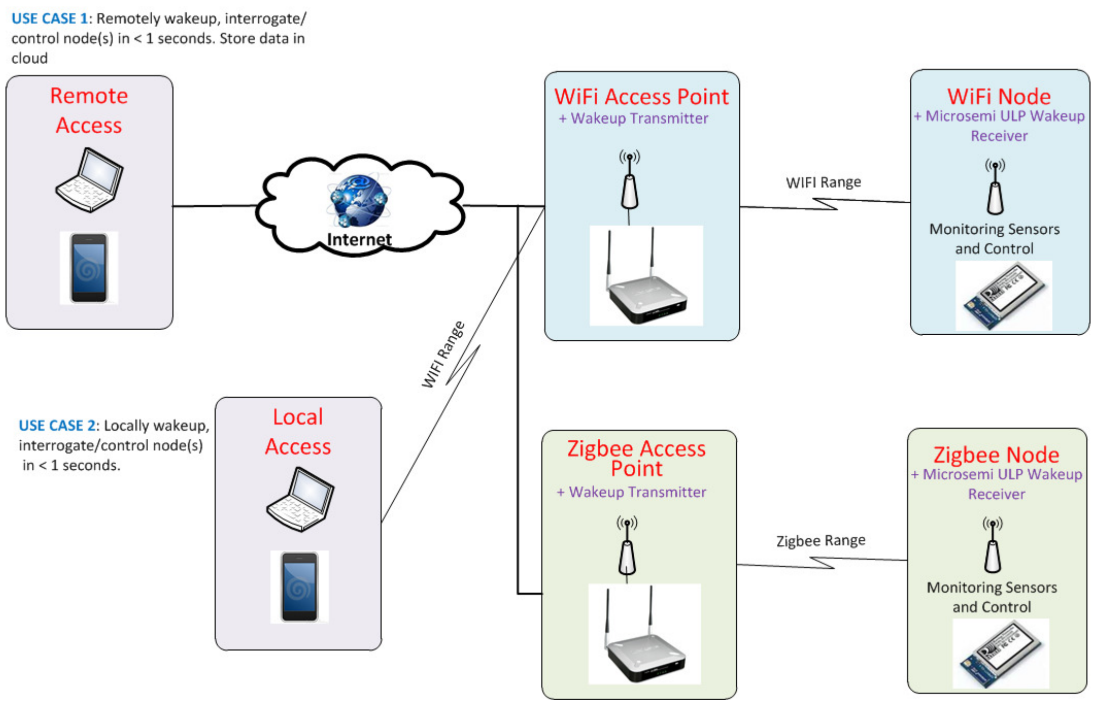

Figure 3: *Wakeup radio use cases*

Wakeup Radio Key Requirements

Wakeup radio requirements will depend heavily on actual use cases with many influences affecting the final specifications, including battery characteristics, ability to recharge or energy harvest, application power demands, required start-up and communication latency, communication usage, sensitivity, and interferer handling.

As an example, consider a 220 mAh CR2032 button cell with 50% of power allocated to communications. Of the 110 mAh available for communications, let's say we can spend half of this for wakeup, so we have an approximately 55 mAh budget. If the sensor node has a five-year lifetime, the average current consumed by wakeup must not exceed 55 mAh / (5x365x24) = 1.3 µA.

Average currents in the sub 2-4 µA range are typical for wakeup systems. Such low currents should be maintained while providing comparable sensitivity to the main radio communication and reasonable interferer rejection.

Comparison Of Wakeup Radio Solutions

Two general strategies exist for implementing low current wakeup radios.

Always on radio: One option is to design an extremely low power transceiver that is always on. For low current budgets in the sub 10 µA range, such radios have very poor sensitivity in the range >-40 dbm. This is inadequate for many applications where the wakeup range should be similar to the normal communication operating range (<-90 dBm).

Sniffing radio: In this option, a typically battery powered, low power radio is duty cycled or sniffs for a wanted communication at a sniff interval less than the required latency. The great benefit of this approach is that decent sensitivity and low power consumption are simultaneously achieved.

In summary, the always-on radio may operate in energy harvesting applications due to the extremely low power required, while the sniffing radio with more challenging sensitivity requirements is used in battery powered applications. The broader range of achievable sensitivities makes the sniffing wakeup radio the more commonly applicable approach.

Roberts in 2012 [3] surveyed a range of devices in the literature and produced a plot similar to that shown in Figure 4, which shows the sensitivity versus power consumed for the two radio types where the always-on radio harvests power and the sniffing radio consumes power from a battery source. The desired wakeup specifications of sensitivities in the range of <-90 dBm and average power levels less than 10 µW is achieved by duty-cycling the power consumed by low power battery operated radios, which may consume thousands of µW when operating at 100% duty cycle. Note that a floor of around 50 µW is seen as a minimum needed to power RF circuitry and produce gain. It is also important to consider that other performance metrics such as interferer handling push many practical systems above the red line indicated in Figure 4. All standard protocols such as ZigBee and Bluetooth operate well above this line. The figure shows that duty-cycling factors of greater than 1/100 are needed to reduce the power consumed into the sub 10 µW region.

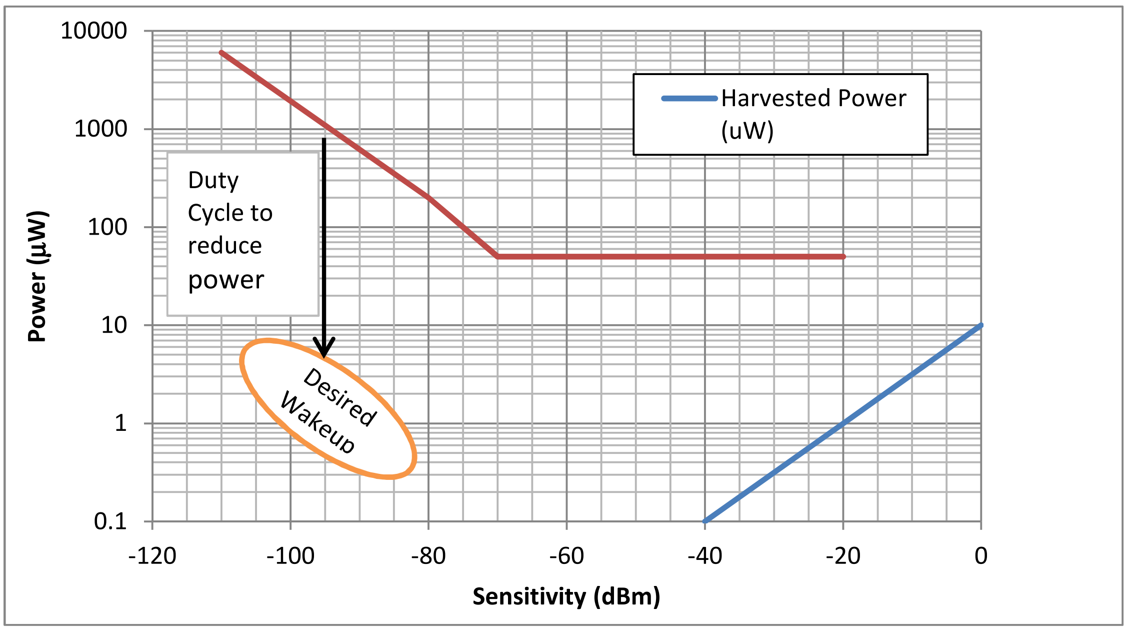

Figure 4: *Power consumed vs. sensitivity for low power radios*

As an example, consider a low power radio with a receiver operating current (I_{RX}) of 5 mA, a sniff time (T_{sniff}) of 1 ms. The average current for a single channel sniff (I_{sniff}) that occurs with a period T_p = 1 second is given by:

Isniff = I_{RX}x(T_{sniff}/T_p)

= 5 mA x0.001/1

= 5 µA.

Many of the existing radio standards do not adequately address the challenge of wakeup radio requirements. As an example for Wi-Fi, if we model the current consumption of a typical Wi-Fi radio configured for a sensor node application with transmission of data every 5 minutes and sniffing for a variable time from 1 second to 1000 seconds, the expected longevity from a AAA battery where 80% of power is used by the application is shown below in Figure 5. The figure indicates that, especially for lower sniff intervals less than 20 seconds, the longevity is poor. For some applications the labor cost of battery replacement may be too high or sensor accessibility issues may exist. The system is especially poor performing when short latencies of ~1 to 2 seconds are required.

A comparison of Wi-Fi, Bluetooth Low Energy (BLE), and a dedicated 2.45 GHz wakeup technology developed by Microsemi are shown in Table 1. BLE uses an advertising mode for startup, and the current consumption was modeled using best in class power consumption devices. The dedicated 2.45 GHz wakeup technology by Microsemi is a proprietary device intended to significantly reduce power consumption for wakeup applications while maintaining good sensitivity.

While BLE is significantly better than Wi-Fi, its wakeup performance for some applications will be inadequate. For example, a 220 mAh CR2032 button cell with 50% of power allocated to communications will have 110 mAh to spend, of which say half may be used for wakeup, so we have an approximately 55 mAh budget. From Table 1, sniffing every second BLE will consume 20 uA on average, which will give a longevity of 2800 hrs or only 117 days. Systems that operate an order of magnitude longer (in the years) are often required. Note that BLE was designed for low frequency communications rather than this specific asynchronous wakeup.

The next section will briefly describe a dedicated asynchronous wakeup system with improved performance.

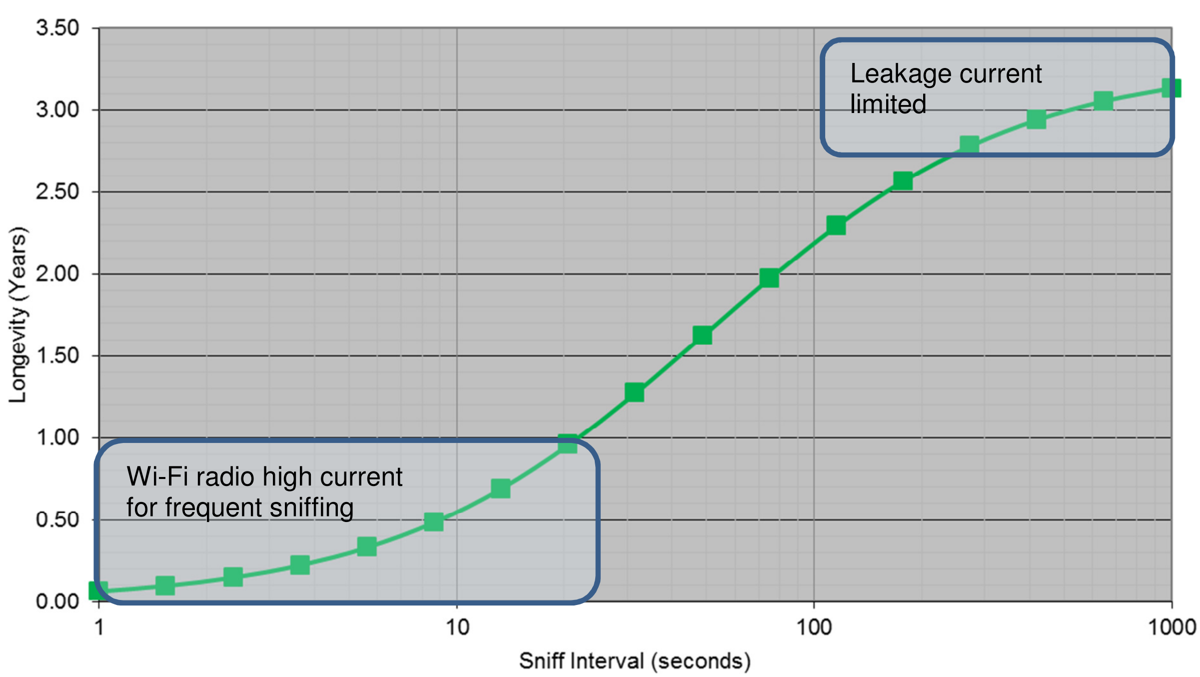

Figure 5: *Wi-Fi longevity vs sniff interval*

Table 1: Comparison of wakeup performance

Technology	Ave. Sniff Current(uA) 1 sniff per second	Sensitivity (dBm)
Wi-Fi	426	-94 to -85
Bluetooth Low Energy	19.5	-92 to -87
Microsemi 2.45 GHz wakeup	3.5	-90

Improved Wakeup Radio Solution

A dedicated wakeup radio may significantly reduce the current consumption of various radio systems, especially the higher power systems such as Wi-Fi. Microsemi's medical products group, which specializes in ultra-low power communications, has developed 2.45 GHz wakeup radio technology, extending on its work in medical implant wakeup radios. The new technology offers significant improvements over previous developments in terms of simultaneously achieving good sensitivity, very low average current, and good interferer handling.

An example configuration of the system within a low power wireless node is shown in Figure 6. The system uses a very simple low cost transmitter to generate a unique FSK pattern that avoids false alarms. In wakeup radio design, there is a trade-off between false alarms and detection time/current, and the design rapidly eliminates false alarms due to the unique characteristics of the transmitted pattern. The wakeup receiver sniffs at a user programmable time (say every second) and enables the host system and radio whenever a valid wakeup pattern is detected.

The device is a very small footprint (<8 mm^2), and the system is a simple addition to both the node and transmitting hub. The improvement in system longevity can be very significant as shown in Figure 7.

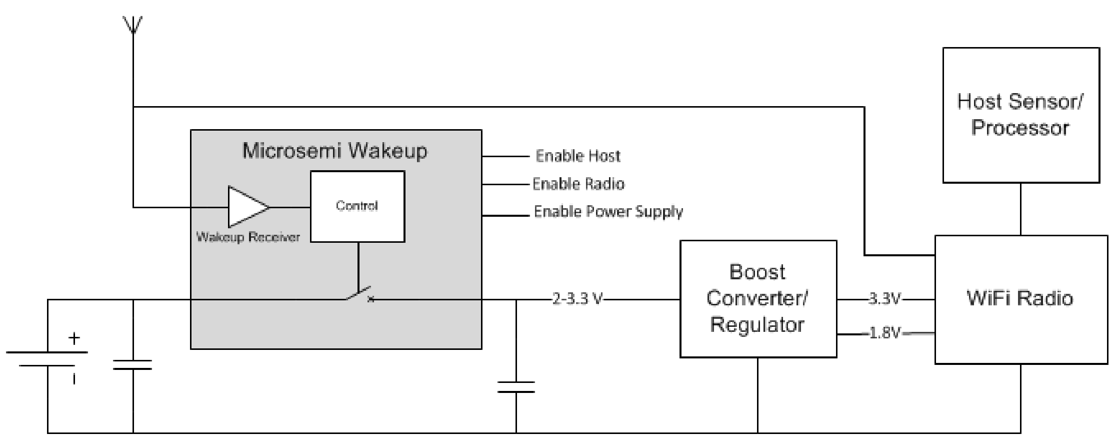

Figure 6: Microsemi 2.45 GHz wakeup – example node system

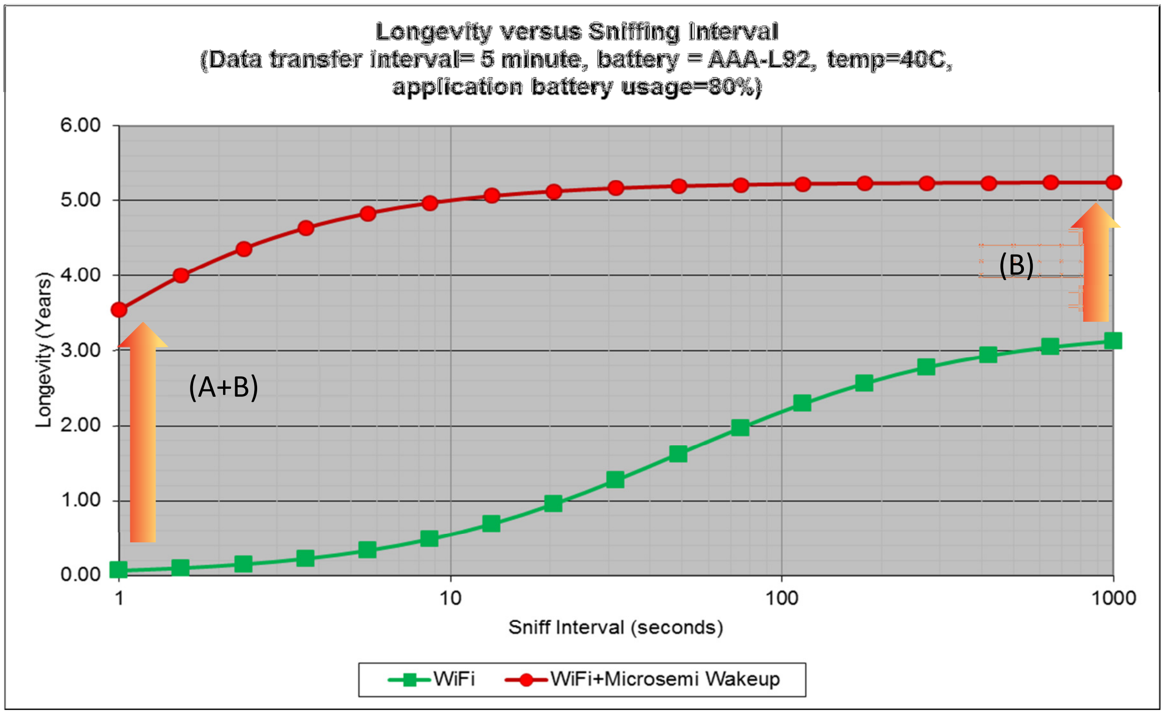

Figure 7: *Improvement in Wi-Fi longevity using dedicated wakeup radio (A = wakeup radio, B = power switch + leakage current reduction)*

Summary

Existing sensor communication protocols (especially Wi-Fi) may drain batteries due to high startup/sniffing currents and excessive leakage currents resulting in unacceptable node longevity and frequent battery replacements. This is particularly evident when use cases demand a fast user response in the range (0.2-30 seconds). In such use cases, dedicated wakeup radios can be good solutions to maintain low average current in ultra-low power nodes.

A wakeup system that may improve wakeup performance to an average current of 3.5 uA for 1 second latency is presented while still maintaining good sensitivity and interferer rejection properties. As an example, the system can improve battery life in Wi-Fi by more than 50x from 23 days to 3.5 years for 1 second response time (using L92-AAA battery) using a simple upgrade on existing designs. Such low power technology is an enabler for the growth of wireless medical implants.

References:

[1] P.D. Bradley, "An ultra low power, high performance Medical Implant Communication System (MICS) transceiver for implantable devices", Biomedical circuits and systems conference, BioCAS 2006.

[2] Microsemi/Zarlink, ZL70102, website, http://www.microsemi.com/products/ultra-low-power-wireless/implantable-medical-transceivers/zl70102.

[3] N. Roberts, D. Wentzloff, "A 98 nW wakeup radio for wireless body area networks", 2012 IEEE Radio Frequency Integrated Circuits Symposium.