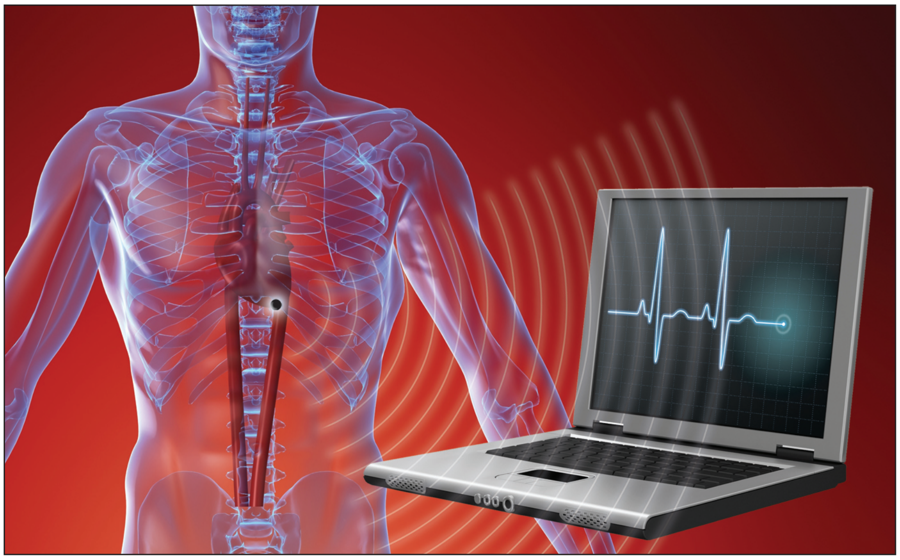
Implantable ultralow-power radio chip facilitates in-body communications

Targeting implantable applications like pacemakers, nerve stimulators, drug pumps, and other such medical devices, an ultralow-power RF transceiver chip has been developed that delivers high data rates, low power consumption and unique wake-up circuitry. This article discusses the design of an in-body communication system.

By Peter D. Bradley

The development of integrated circuits (ICs) and medical devices has evolved in concert over the past 30 years. Circuit technology has facilitated the evolution of increasingly complex, highly integrated and smaller medical devices. At the same time, burgeoning healthcare costs combined with a more affluent, more obese and longer-living population, has created demand for new applications and therapies relying on implanted medical devices that are wirelessly linked to base stations.



Brief history

Traditionally, communication systems in implanted medical devices have used very short-range magnetic coupling. This required close coupling between the programmer and medical device and often delivered data rates of less than 50 kbps.

To overcome the range limitations, the 402 MHz to 405 MHz medical implant communication service (MICS) band was established in 1999, with similar standards following in Europe[1,2]. This band supports the use of longer range (typically two meters), relatively high-speed wireless links. The 402 MHz to 405 MHz band is well suited for this service, due to the signal propagation characteristics in the human body, compatibility with the incumbent users of the band (meteorological aids such as weather balloons), and its international availability (Figure 1).

Electronic systems for implanted medical applications present formidable low-power design challenges. For example, most implanted pacemakers have lifetime requirements of greater than seven years with maximum current drains on the order of 10 µA to 20 µA. The communication systems are budgeted at total currents averaged over the device lifetime of no more than about 15% of the total power budget or 2 µA to 3 µA due to the current consumption demands of supporting pacing therapy. Receivers in implanted medical systems must periodically "sniff" or monitor for an external communication device, and conserve power by remaining off in a very low power state when not sniffing.

Design considerations

To enable the use of the MICS band, implanted medical devices require an ultralow-power, high-performance transceiver. Implanted device transceiver design faced numerous challenges:

- Low power during 400 MHz communications. Implant battery power is limited and the impedance of implant batteries is relatively high. This limits peak currents that may be drained from the supply.
- During communication sessions, current should be limited to less than 6 mA for most implantable devices.
- Low power when asleep and periodically "sniffing" for a wake-up signal.
- Minimum external component count and physical size. Implant-grade components are expensive and high levels of integration may reduce costs and increase overall system reliability.
- Reasonable data rates. Pacemaker applications are currently demanding >20 kbps, with much higher data rates projected for the future.
- High system and data transmission reliability.
- Selectivity and interferer rejection especially from TETRA radios in Europe.
- Typically greater than two-meter range. Longer ranges imply good sensitivity is needed since small antennas and body loss affect link budget and allowable range. Antenna, matching, fading and body losses are quite variable with losses as high as 40 dB to 45 dB.

The ZL70101 MICS transceiver offers exceptionally low power consumption while providing a high data rate. The transmit and receive current is less than 5 mA when operating at a data rate of up to 800 kbps. The circuit features a unique ultralow-power wakeup system operating at 2.45 GHz that enables an average sleep/sniffing current of less than 250 nA. System integration is high and only three external components (crystal and two decoupling capacitors) and a matching network are required.

Medical devices may be categorized into those that use an internal non-rechargeable battery (e.g., pacemakers) and those that couple power inductively (e.g., cochlea implants). The former heavily duty-cycle the operation of systems to conserve power. The transceiver is off most of the time, therefore, the off-state current and the current required to periodically look for a communicating device must be extremely low (<1-2 µA). In both cases, low power (<6 mA) for transmit and receive is also required.

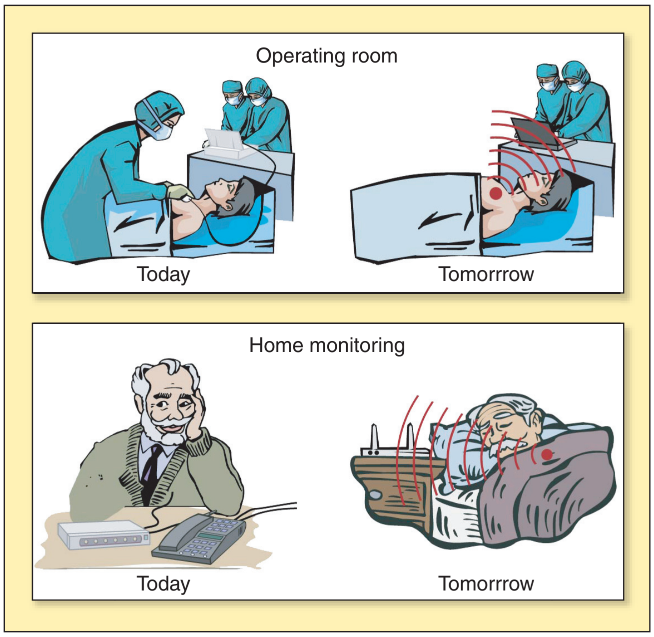


Figure 1. Benefits of MICS band.

The ZL70101 has a peak Rx/Tx current consumption of <5 mA operating from a supply voltage of between 2.1 V to 3.5 V. This current includes the basic RF transceiver and MAC current. The MAC ensures the user receives high integrity data and automatically performs much of the required link maintenance. Furthermore, the MAC protocol offers a power-save timer that turns off the receiver in the implant for a programmable time after transmitting a packet.

For minimum overall power consumption, defined in terms of Joules/bit, it is recommended that implantable transceivers should use the highest possible data rate that satisfies the application receiver sensitivity requirements. Systems that require low data rates (even in the low kHz range) should buffer data, operate at the highest data rate possible and exploit duty cycling to reduce the average current consumption. Sending data in short bursts conserves power and reduces the time window allowed for interference. In addition, in systems with high battery impedance the power supply decoupling requirements may be more forgiving due to shorter bursts of charge drawn from capacitors.

The transceiver allows the user to select from a wide range of data rates (200 kbps, 400 kbps, 800 kbps) with varying receiver sensitivity. To facilitate this flexibility, the system uses either 2 FSK or 4 FSK modulation with 200 or 400 ksymbols per second and varying frequency deviations (Table 1). Lower data rates and correspondingly higher receiver sensitivity may be attained by off-chip digital filtering. The transceiver has a MAC bypass mode of operation in which the radio is fully accessible. In this configuration, the user may develop customized protocols and data rates.

Modulation Mode	Data Rate (kbps)	Receiver Sensitivity (µVrms)	Receiver Sensitivity (dBm)
2 FSK	200	<14	-99
2 FSK	400	<25	-94
4 FSK	800	<80	-84
Note: The effective impedance at the Rx input is higher (~1600 Ω).			

Table 1. Data rate vs. receiver sensitivity.

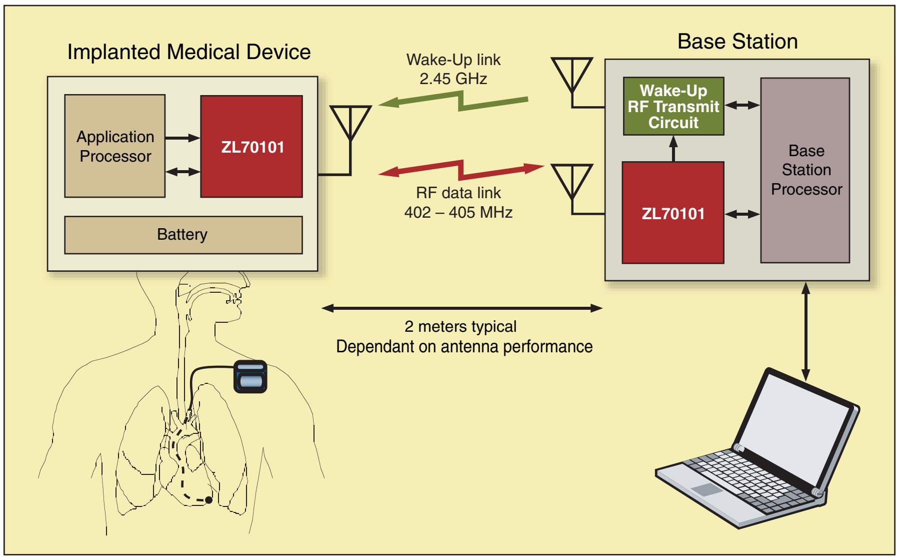


Figure 2. Overall system architecture with the ZL70101 MICS transceiver operating in the implanted medical device and base station.

Overall system architecture

The ZL70101 operates in the implanted device and external base station (Figure 2). The base station includes additional circuitry to transmit a 2.45 GHz wake-up signal. Once the system is started via the 2.45 GHz wake-up signal, data is exchanged using the 402 MHz to 405 MHz MICS band transceiver.

The ZL70101 MICS chip (Figure 3) consists of three main subsystems: a 400 MHz transceiver, a 2.45 GHz wake-up receiver and a media access controller (MAC). The chip may be used as the transceiver in either an implanted medical device or a base station programmer as determined by the state of an input pin.

The transceiver uses a low intermediate frequency (IF) superheterodyne architecture with image reject mixers. The low-IF minimizes filter and modulator power consumption without the flicker noise and dc offset problems associated with high data rate, zero-IF architectures. An FSK modulation scheme reduces Tx amplifier linearity requirements, thereby reducing power consumption and allowing for a simpler limiting receiver.

The 400 MHz transmitter subsystem, labeled half-duplex RF transmitter shown in Figure 3, consists of an IF modulator, mixer and power amplifier. The IF modulator converts a one-bit (2 FSK) or two-bit (4 FSK) asynchronous digital input data stream to an intermediate frequency. An upconverting mixer transforms the IF to RF frequency. Note that the local oscillator frequency is the

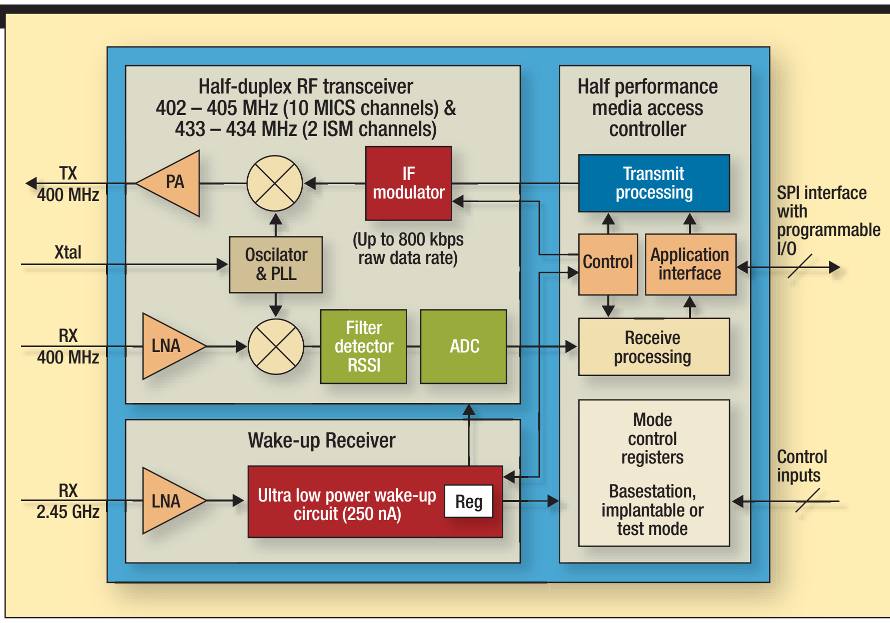


Figure 3. Block diagram of ZL70101 MICS transceiver showing the three main subsystems: a 400 MHz transceiver, a 2.45 GHz wake-up receiver and a media access controller (MAC).

Parameter	Specification
Technology	0.18 um RF CMOS
Supply voltage	2.1 V – 3.5 V
Radio frequency	402 MHz – 405 MHz (10 ch. MICS), 432 – 434 (2 ch. ISM)
Max. raw data rate	800 kbps
400 MHz sensitivity at 200 kbps	–99 dBm
Current (Tx/Rx)	5 mA
Current (sleep + sniffing)	250 nA
Estimated range	>2 meters
Final BER, block data (assuming raw radio BER 10^{-3})	<1.5×10^{-10} errors/bit

Table 2. Measured performance summary.

same for transmit and receive mode, which minimizes dead time between receiving and transmitting packets.

The output power of the Tx power amplifier is register programmable in <3 dB steps from -4.5 dBm to -17 dBm (into a 500 Ω load). Internal antenna-matching capacitor banks on all RF inputs allow for fine-tuning the matching network for maximum delivered output power for a given power setting and optimum receiver noise figure. The antenna tuning is an automatic calibration that uses a peak-detector coupled to an ADC along with a state-machine for calibration control.

The 400 MHz receiver subsystem amplifies the MICS band signal and downconverts from the carrier frequency to the IF. The low-noise amplifier (LNA) gain is programmable from 9 dB to 35 dB. Higher gain settings are recommended for implanted medical device transceivers while the lower gain settings may be applicable to base station transceivers that choose to use an external LNA. Programmability of LNA and mixer bias currents provides further flexibility in optimizing for desired linearity (IIP3), power consumption and noise figure.

A polyphase IF filter is used to suppress interference at the image frequency and adjacent channels and limit the noise bandwidth. Limiters and a received signal-strength indicator (RSSI) block follow the polyphase filter. The RSSI measurement is converted by a five-bit ADC and may be read by the industry-standard SPI interface. This is useful for performing the MICS clear-channel assessment procedure. Note that an external instrument must first determine a suitable usable channel via a process of clear-channel assessment defined in the MICS standards.

A specific protocol customized for high reliability medical applications has been developed. This protocol is handled by the MAC and includes the following main features:

■ Correction and detection of errors using Reed-Solomon forward error correction (FEC) and cyclic redundancy code (CRC) error detection. The effective BER after FEC and CRC is better than 1.5×10^{-10} given a raw radio BER of 10^{-3}.

■ Automatic retransmission of data blocks in error and flow control to prevent buffer overflow.

■ Capable of sending MICS emergency command and high priority messages.

■ Handling of link watchdog to ensure link is shutdown after five seconds without successful communication.

■ Provision of link quality diagnostics and control of automatic calibrations.

Ultralow-power wake-up receiver

Most implant applications will infrequently use the MICS RF link due to the overriding need to conserve battery power. In very low-power applications, the transceiver will be asleep in a very low current state for the majority of the time. Systems that use the MICS band must wait for the base station to initiate communications following a clear channel assessment procedure, except when sending an emergency command. Periodically, the implanted transceiver should listen for a base station that wants to begin communication.

The wake-up system uses an ultralow-power RF receiver operating in the 2.45 GHz SRD band to detect and decode a specific data packet that is transmitted from a base station and then switch on the supply to the rest of the chip. The chip may also be started directly by pin control as would be needed for a base station starting up, an implant sending an emergency command or an implant using an alternative wake-up system.

Conclusion

Ultralow-power wireless technology is key for a range of implanted medical devices, including pacemakers, defibrillators, neurostimulators, drug infusion systems, diagnostic sensors and the rapidly growing implanted diabetes monitor. However, as implanted communication systems evolve to support advanced diagnostics and therapies, it's critical that wireless performance does not impact the battery life of an implanted medical device.

References

1. FCC rules and regulations 47 CFR Part 95, subparts E (95.601-95.673) and I (95.1201-95.1219) Personal Radio Services, November 2002.

2. ETSI EN 301-839, parts 1 and 2 and ETSI EN 301-489 part 27.

ABOUT THE AUTHOR

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