An Ultra Low Power, High Performance Medical Implant Communication System (MICS) Transceiver for Implantable Devices

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Abstract—A 402-405 MHz MICS band transceiver has been developed for implantable medical applications. The transceiver offers exceptionally low power consumption whilst providing a high data rate. The circuit features a unique ultra low power wakeup system enabling an average sleep current of less than 250 nA. The transmit and receive current is less than 5 mA when operating at a data rate of up to 800 kbps. System integration is high and only 3 external components (crystal and 2 decoupling capacitors) and a matching network are required. The transceiver can also operate in the 433 MHz ISM band. The key system design features and performance of this transceiver are presented in this paper.

I. INTRODUCTION

Traditionally, communication systems in medical devices have used very short-range magnetic coupling. These systems require close coupling between the programmer and medical device and often have limited available data rate.

The 402-405 MHz Medical Implant Communication Service (MICS) band was recommended for allocation by ITU-R Recommendation SA1346 in 1998. The FCC established the band in 1999 with similar standards following in Europe [1,2]. The allocation of this band supports the use of larger range (typically 2 meters), high-speed wireless links. The MICS band overcomes the limitations of dated inductive systems and facilitates the development of next generation medical devices with improved patient health care. This is especially important given escalating health costs driving the usage of home monitoring.

The 402-405 MHz band was considered well suited for this service, due to the signal propagation characteristics in the human body, the compatibility with the incumbent users of the band (Meteorological aids such as weather balloons), and its international availability for this purpose.

To enable the use of the MICS band, medical devices require an ultra low power, high performance transceiver. This paper presents a transceiver integrated circuit (IC) specifically designed for this purpose. The design considerations of implantable transceivers are presented, followed by a brief discussion of the architecture and important design features.

II. TRANSCiever DESIGN CONSIDERATIONS

The design of transceivers for medical devices is challenged by the following basic requirements:

- Low power during 400 MHz communication is required. 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 looking for a wakeup signal is required.
- Minimum external component count and minimum physical size are important factors. An RF module for a pacemaker must be no more than ~3x5x10 mm³. Furthermore, implant grade components are expensive and using high levels of integration may significantly reduce costs. Integration has the additional benefit of increasing overall system reliability.
- Reasonable data rates are demanded, pacemaker applications are currently demanding >20 kbps with higher data rates projected for the future.
- High system and data transmission reliability.
- Selectivity and interferer rejection especially from TETRA radios.
- Typically greater than 2 meter range since the MICS band is designed to improve upon the very short range inductive link. 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 40-45 dB.

The transceiver presented in this paper addresses all of these requirements. Some specific tradeoffs and the device performance are discussed below.
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 and 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.

The transceiver presented has a peak RX/TX current consumption of <5 mA operating from a supply voltage of between 2.1-3.5 V. This current not only includes the basic RF transceiver current but also the MAC (Media Access Controller) current. The MAC ensures the user receives high integrity data and performs much of the required link maintenance automatically. 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. This is especially useful if the implant momentarily has no information to send and would like to conserve power.

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 of the power states to reduce the average current consumption. Sending data in short bursts not only conserves power. In addition, the time window allowed for interference is reduced by a short transmission time, and, in systems with high battery impedance, the power supply decoupling requirements may be more forgiving.

The transceiver allows the user to select from a wide range of data rates (200-400-800 kbps) with varying receiver sensitivity. To facilitate this flexibility, the system uses either 2FSK or 4FSK modulation with 200 or 400 kSymbols/s and varying frequency deviations. The table below summarizes the allowable modulation modes, respective data rates and corresponding receiver sensitivity. 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.

### Table 1. Data Rate vs Receiver Sensitivity

<table>
<thead>
<tr>
<th>Modulation Mode</th>
<th>Data Rate (kbps)</th>
<th>Rx Sensitivity (µV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4FSK</td>
<td>800</td>
<td>&lt;90</td>
</tr>
<tr>
<td>2FSK-high rate</td>
<td>400</td>
<td>&lt;35</td>
</tr>
<tr>
<td>2FSK- high deviation</td>
<td>200</td>
<td>&lt;20</td>
</tr>
</tbody>
</table>

Note: The effective impedance at the RX input is high (≈1600 ohms).

### III. Transceiver Architecture

The chip, as shown in figure 1, consists of 3 main sub-systems; a 400 MHz transceiver, a 2.45 GHz wake-up receiver and a media access controller (MAC). The purpose and basic architecture of each of these sub-systems is now described. The chip may be used as the transceiver in either an implanted medical device (IMD) or a base-station programmer as determined by the state of the IBS pin.

#### A. 400 MHz Transceiver

The transceiver uses a low-intermediate frequency super-heterodyne 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 allows for a simpler limiting receiver.

The 400 MHz transmitter subsystem consists of an IF modulator, I and Q mixer and power amplifier. The IF modulator converts a one (2FSK) or two bit (4FSK) asynchronous digital input dat stream to a 450 kHz FSK modulated I and Q signal. An up-converting mixer transforms the IF to RF frequency. Note that the local oscillator frequency is the same for both transmit and receive mode, which minimizes dead time between receiving and transmitting packets. Both low and high side injection are used to always keep the image in the MICS band. This relaxes the demands on phase and amplitude matching of the I and Q signals.

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 ohm load). An antenna matching capacitor bank is provided to fine tune the matching network for maximum delivered output power for a given power setting. The antenna tuning is an automatic calibration which 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 down-converts from the carrier frequency to the intermediate frequency (IF) using an IQ image reject mixer. The LNA gain is programmable from 9 to 35 dB. Higher gain settings are recommended for IMD transceivers whilst 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.

An image rejecting I/Q poly-phase 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 poly-phase filter. The RSSI measurement is converted by a 5 bit ADC and may be read by the SPI interface. This is useful for performing the MICS clear-channel assessment procedure.

The Frequency Synthesizer is a PLL structure with a RF Voltage Controlled Oscillator (VCO) running at four times the LO frequency. The I/Q Local Oscillator (LO) signals are derived from the VCO signal and distributed to the receive and transmit Front-End. The channel number is programmable from 1-10 for the 402-405 MHz MICS band and 11-12 for the 433.65 and 434.25 MHz ISM band.

A 24 MHz crystal was selected as a compromise between small implant crystal size (decreases slowly with increasing frequency) and oscillator power requirements (~200 µA budgeted). Moreover, this frequency simplifies on-chip clocking since 24MHz/80= 300 kHz is exactly the channel spacing and 24 MHz/60 = 400 kHz is the symbol rate. The trimming method uses a frequency locked loop technique that requires an accurate external RF source. By using an RF reference source the calibration may be easily performed on a fully manufactured IMD without contacting the device. Most calibrations required for the system are automatic and handled internal to the chip. Four calibrations require external equipment and all are contact-less; RSSI calibration, antenna tuning, the power amplifier calibration, which requires a power meter, and the above mentioned crystal oscillator calibration. Contact-less calibrations are advantageous in a medical implant manufacturing and enable calibration on the final sealed product.

B. Ultra Low Power Wakeup System

Most implant applications will use the MICS RF link infrequently due to the overriding need to conserve battery power. In very low power applications, the transceiver will spend most of the time asleep in a very low current state. Except for the sending of an emergency command, systems that use the MICS band must first wait for the base to initiate communications following a clear channel assessment procedure in which the base determines which channel to use. Therefore, periodically, the IMD transceiver should listen for a base that wants to begin communication. This "sniffing" operation should be frequent enough to provide reasonable startup latency, consume a very low current since it will occur regularly, and be immune to noise sources that invoke an erroneous startup.

For a very low power receiver, an OOK modulation scheme is recommended since it removes the need for a local oscillator and synthesizer in the receiver. Further simplification, and hence power saving, is gained by using a frequency band for the startup process which is of reasonable power. The 2.45 GHz short range device (SRD) band satisfies such a requirement and at 100 mW EIRP (in USA, 10 mW in a few countries such as Japan) is up to 36 dB higher in power than the 25 uW MICS.

The wakeup system uses an ultra low power RF receiver, operating in the 2.45GHz SRD-band, to read OOK transmitted data. The main function is 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 data packet contains transceiver setup information. The chip may also be started directly by pin control as would be needed for either a base starting up, an implant sending an emergency command or an implant using an alternative wakeup system. For example, one such alternative wakeup system is to use the available RSSI measurement facility to sense a Base 400 MHz communication.

To reduce the average current consumption of the wakeup subsystem, the wakeup system is strobed by either an application generated strobe pulse applied to a pin or an internally generated strobe pulse created using a low power (<400 nA) internal 25kHz oscillator. The user selects an interval between strobes (Twu.period) dictated by the application’s required wakeup latency and the average current consumption which for external strobing is given by

\[ I_{DD}(average) = 100 \text{ nA} + 715 \times 240 \times 10^{-12} / T_{wu.period} \]

where the...
2.45 GHz RX consumes a maximum of 715 µA when sniffing.

In the example calculation supplied in fig. 2, 250 nA (external strobe) or 650 nA (internal strobe) is achieved including 100 nA budgeted for leakage current. The calculation in this example assumes a time between strobes of 1.15s. Actual measured leakage current at room temperature is less than 10 nA so the 100 nA budget is a very conservative design buffer.

\[ T_{S/W,\text{on}} > 240 \mu s \]
\[ T_{W,\text{pulsed}} = 1.15 \text{s} \]
\[ I_{\text{DD,(min)}} = 715 \mu A \]
\[ I_{\text{DD,(max)}} = 250 \text{ nA} \]
\[ I_{\text{DD,(min)}} = 100 \text{ nA} \]

Figure 2. Example current consumption of low power wakeup system

IV. MEDIA ACCESS CONTROLLER

A specific protocol customized for high reliability medical applications was developed. This protocol is handled by the MAC which consists of 4 main sub-systems including transmitter processing, receiver processing, communication control and application interface.

The communication control implements and controls the overall transceiver communication protocol. The features offered by the protocol include:

- Correction and detection of errors (FEC and CRC). The effective BER after FEC and CRC is better then \(1.5 \times 10^{-10}\) given a raw radio BER of \(10^{-7}\).
- 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 5 seconds without successful communication
- Provision of link quality diagnostics and control of automatic calibrations

The rich feature set of the communication protocol relieves the user application of many link maintenance activities. The communication link is simply viewed as a receive and transmit buffer accessible via the SPI interface. Buffer conditions that require user attention are flagged by interrupts allowing the user to optimally maintain data flow.

The transmit processing is fed by a storage buffer capable of storing 2 maximally sized packets with 31 data blocks. Data packets consist of between 1-31 data blocks (user programmable) with each data block 14 bytes. The buffer is simply a memory mapped address that is written through the SPI interface. The TX control will construct a data packet when 1 or more data blocks exists in the transmit buffer. A cyclic redundancy code (CRC) is appended to the data and the result is passed through a Reed-Solomon block that provides extensive forward error correction. The final stage of transmission processing is to perform whitening using a pseudo-noise (PN) method. Whitening ensures that the data has sufficient transitions for accurate operation of the clock recovery.

The receiver processing fills up a storage buffer capable of storing 2 maximally sized packets. Again, the buffer is simply a memory mapped address that is read through the SPI interface. The receiver performs clock recovery by oversampling the received data and identifies the correlation word signifying the start of a packet. Upon receipt of a packet, a Reed-Solomon decoder performs forward error correction on the header and each of the blocks that constitute a packet. The RS is capable of correcting up to 15 bits within a block. After error correction, a CRC decoder determines blocks which contain uncorrectable errors and forwards the information on which blocks require retransmission to the transmit controller and main sequencer.

V. CONCLUSION

An ultra low power high performance transceiver for implanted medical applications is presented. The transceiver is highly integrated and includes a complete media access controller that provides the user application with a high effective BER. The key RF performance parameters are summarized below. Given these performance capabilities the communication systems of future generation medical devices will be significantly enhanced.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td>0.18 um RF CMOS</td>
</tr>
<tr>
<td>Supply Voltage</td>
<td>2.1-3.5 V</td>
</tr>
<tr>
<td>Radio Frequency</td>
<td>402-405 MHz (10 ch.)</td>
</tr>
<tr>
<td></td>
<td>432-434 (2 ch.)</td>
</tr>
<tr>
<td>Max Raw Data Rate</td>
<td>800 kbps</td>
</tr>
<tr>
<td>400 MHz Sensitivity @ 200 kbps</td>
<td>&lt;20 µV rms</td>
</tr>
<tr>
<td>Current (TX/RX)</td>
<td>&lt;5.5 mA</td>
</tr>
<tr>
<td>Current (Sleep+sniffing)</td>
<td>&lt;250 nA</td>
</tr>
<tr>
<td>Estimated Range</td>
<td>&gt;2 Meters</td>
</tr>
<tr>
<td>Final BER, block data (assuming raw radio BER 10^{-3})</td>
<td>&lt;1.5×10^{-10} errors/bit</td>
</tr>
</tbody>
</table>

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REFERENCES