Implantable and Wearable Bioelectronics Systems: Can We Use Wideband Technology?

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Outline

- Introduction
- Implantable Bioelectronics
  - Power
  - Data transfer methods
- Multi-Channel Recording and Monitoring
  - Multi-channel EEG, ECG (Pacemaker) recording.
- Electronic Pill
- Conclusion
Time Line of Implant Technology

- **ANCIENT TIMES**
  - Prosthetic Limbs
  - Better Prosthetic Limbs

- **Iron/Wood Work**

- **Titanium**

- **1970s**
  - Pacemaker
  - Cochlea Implant

- **Plastics**

- **Electronics and IC Technology**

- **Advanced RF Technology**

- **NOW**
  - Bionic Eye
  - Implantable Telemetry (electronic pill, pH, temp. etc.)
  - Robotic Limbs
  - Intelligent Health Care Systems (WBAN)

- **1957** - First Wearable pacemaker (in 1958 fully implant)
- **1984**, the **Australian cochlear implant** approved by FDA
- **2000**, First clinical trial wireless endoscope (electronic pill)
Implantable systems: Bionic Eye, Cochlear Implant, pacemaker etc.
Implantable Prosthesis

Involves sending a signal to the body can not perform.

- Muscular Stimulation
- Nerve Stimulation

Implantable systems:
Bionic Eye, Cochlear Implant, pacemaker.
Cochlear implant (Bionic Ear)

- Electrical stimulation in the auditory system for perception of sound.
- Sound information over a wireless link to the internal section of the device.
- An electrode arrays is used to stimulate the regions of the auditory nerve.

Credit: NIH Medical Arts: Ear with Cochlear implant
Implantable Telemetry

- Telemetry involves sensing information and transmitting it externally for monitoring.
- It is a widely established field, used in cardiac defibrillators, cardiac monitoring and animal research
- Temperature, Heart Signals, Blood Pressure in Body Area/Sensor Networks, Health-Care systems
Wireless Body Area Network

**Current application of WBAN**
- Body area network targets both implanted and external nodes.
- A system that is defined to control wearable and implantable wireless biodevices around the human body.

**Future application of WBAN**
- Sensor node electronics with wireless capability
- CCU acts as an intermediate wireless node to connect other wireless technologies at remote monitoring locations.
• An interference free wireless medical network for monitoring physiological parameters in a hospital environment may be quite challenging since there are a number of other wireless systems (e.g. Wi-Fi, Bluetooth, ZigBee, Microwave oven) operating already for different purposes.
Wireless Power Transfer

- Power has been traditionally supplied using batteries (Lithium and Li-ion).
- This is the case for Pacemakers, where surgery must be performed just to replace batteries.
- External wireless power was therefore a great development in this area, and several implanted devices are now being either charged externally or directly powered from an external wireless source.
- This wireless charging occurs inductively between coils, similar to a weakly coupled transformer.

<table>
<thead>
<tr>
<th>Powering Method</th>
<th>Implant Type</th>
<th>Frequency</th>
<th>Energy</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductive Batt. Charging</td>
<td>Cochlear</td>
<td>150 kHz</td>
<td>(75mAh)</td>
<td>[1] Lim</td>
</tr>
<tr>
<td>Inductive Batt. Charging</td>
<td>General</td>
<td>4 MHz</td>
<td>6.15mW</td>
<td>[2] Li</td>
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<tr>
<td>Direct Inductive Transfer</td>
<td>Retinal</td>
<td>1 MHz</td>
<td>100mW</td>
<td>[3] Wang</td>
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</tbody>
</table>
Inductive Power in Biomedical Implants

- flux pattern of a cylindrical helix coil and planar spiral
- two similarly sized coils in the order of 100mm x 100mm
Power Amplifiers

- Switched-Mode Power Amplifier
  - Used for high-frequency applications because of its high efficiency.
  - Theoretical Efficiency is 100%
  - Practical Efficiency is ~80%

- Class-D, E, F Amplifiers
Wireless Power: Class-E

\[ Z_L = sL_1 \parallel \frac{1}{sC_{11}} \parallel \left( \frac{1}{sC_2} + sL_2 + R \right) \]

\[ = \frac{s^2L_2C_2 + sRC_2 + 1}{s^3L_2C_1C_2 + s^2(RC_1C_2) + s \left( C_1 + \frac{L_2C_2}{L_1} + C_2 \right) + \left( \frac{RC_2}{L_1} \right) + \frac{1}{sL_1}} \]

L1 is a choke inductor, and if it is assumed to be large, the resonant frequency turns out to be:

\[ \omega = \frac{1}{\sqrt{L_2C_1||C_2}} \]
Parasitic Capacitance of Coils

- Parasitic capacitance exists in all inductors
- Low pF range for coils with diameters in the order of 10mm
- That is comparable with other circuit capacitors at frequencies above 100MHz

\[ C = \frac{\varepsilon_0 2\pi r N \cdot 2a}{l/N} \]
CLASS-E AMPLIFIER
Parasitic Capacitor

- If the Class-E amplifier is remodeled to include the parasitic Capacitor C3, the circuit would appear as shown below.
CLASS-E AMPLIFIER

\[ \omega = \frac{1}{\sqrt{L_2 C_1 || C_2}} \]

\[ \omega = \frac{1}{\sqrt{L_2 (C_1 || C_2 + C_3)}} \]
CLASS-E AMPLIFIER

Circuit

\[ Z_T = sL_1 \frac{1}{sC_1} \left[ \frac{1}{sC_2} + \frac{1}{sC_3} \left( sL_2 + R \right) \right] \]

\[ = sL_1 \frac{1}{sC_1} \left[ \frac{1}{sC_2} + \left( \frac{1}{sC_3} \frac{1}{sL_2 + R} \right)^{-1} \right] \]

\[ = sL_1 \frac{1}{sC_1} \left[ \frac{s^2 L_2 L_3 + sRC_3 + 1 + s^2 L_2 C_2 + sRC_2}{s^3 L_2 C_2 C_3 + s^2 RC_2 C_3 + sC_2} \right]^{-1} \]

\[ = sL_1 \left[ \frac{sC_1 + \frac{s^3 L_2 C_2 C_3 + s^2 RC_2 C_3 + sC_2}{s^2 L_2 L_3 + sRC_3 + 1 + s^2 L_2 C_2 + sRC_2}}{s^2 L_2 L_3 + sRC_3 + 1 + s^2 L_2 C_2 + sRC_2} \right]^{-1} \]

\[ = sL_1 \left[ \frac{s^3 L_2 C_1 C_3 + s^3 L_2 C_1 C_2 + s^2 RC_1 C_3 + s^2 RC_1 C_2 + s^3 L_2 C_2 C_3 + s^2 RC_2 C_3 + sC_2 + sC_1}{s^2 L_2 L_3 + sRC_3 + 1 + s^2 L_2 C_2 + sRC_2} \right]^{-1} \]

\[ = \frac{1}{sL_1} + \frac{s^3 L_2 C_1 C_3 + s^3 L_2 C_1 C_2 + s^2 RC_1 C_3 + s^2 RC_1 C_2 + s^3 L_2 C_2 C_3 + s^2 RC_2 C_3 + sC_2 + sC_1}{s^2 L_2 L_3 + sRC_3 + 1 + s^2 L_2 C_2 + sRC_2} \]

\[ = s^4 L_1 L_2 (C_1 C_2 + C_1 C_3 + C_2 C_3) + s^3 RL_1 (C_1 C_2 + C_1 C_3 + C_2 C_3) + s^2 (L_1 C_1 + L_1 C_2 + L_2 C_2 + L_2 C_3) + sR(C_2 + C_3) + 1 \]

\[ = \frac{s^3 L_1 L_2 (C_2 + C_3) + s^2 RL_1 (C_2 + C_3) + sL_1}{(C_1 C_2 + C_1 C_3 + C_2 C_3)(s^4 L_1 L_2 + s^3 RL_1) + s^2 (L_1 C_1 + L_1 C_2 + L_2 C_2 + L_2 C_3) + sR(C_2 + C_3) + 1} \]

\[ \omega = \frac{1}{\sqrt{L_2 (C_1 || C_2 + C_3)}} \]
CLASS-E AMPLIFIER

20 MHz Class-E Amplifier

- Original Class-E

Self-Resonant Consideration
CLASS-E AMPLIFIER

403-MHz Class-E Amplifier

Original Class-E Equations

Self-Resonant Consideration
Rectification

Half-wave diode rectifier

Full-wave bridge rectifier

Class-E rectifier
Wireless Power-Rectification

- Diode voltage drop: 0.1 to 0.7V
- Sending more power to compensate for the forward voltage drop is possible however SAR should be taken into consideration
- Currently few cm range is possible.
- Can we increase distance with high frequency?
Animal Applications

- Further miniaturization required for small animals.
- An array of spirals connected in series and parallel.
Stacked Spiral
Measured Results

- Comparison between $\text{Re}(Z_{11})$ of the simulated and measured results
 Alternative Power Sources

- ultrasound-based method for powering battery-free implantable devices
- coupling gel can be used to enhance the ultrasonic energy into the body

Energy Harvesting via Ultrasound/MEMs

- Harvesting arbitrary vibration energy
- Detect X and Y movements separately by using electrostatic combs
1N5711, Schottky diodes with 0.2 V voltage drops, 1 μF storage capacitor

The ultrasonic power transmission is relatively safe for the human’s body and does not interfere with electronic devices.
Forward Data Transfer

- Frequencies lower have 20 MHz have been used
- For higher frequencies a down conversion with mixer is required which will add additional power and size the implant
Do we need a complicated receiver? Not really.

☑️ Received signal is strong so is SNR. It is a very short range link.
Forward Data Transfer

- Inductive link transmission/reception for short-range applications
  - Low-frequency is used for forward data transmission (e.g. 13.56 ISM)
Forward Data Transfer

- ASK has been commonly used in early times
- Digital ASK signal is demodulated simply using a frequency divider.
- $f_c = N \times f_b$. 

Diagram:

- Analog ASK Signal
- Digital ASK
- $f_c$: carrier frequency
- $f_b$: bit frequency
- $N$: Frequency divider
- $V_{ref}$: Reference signal
- Demodulated signal
  - "1"
  - "0"
  - $f_c / N$
  - $f_c / 2$
  - Dividing by 2
A PSK based system can also be used.

When non-coherent PSK (DPSK) is used, a loop is not needed for Carrier synchronizations.
Forward Data Transmitter

Power Spectrum

OOK (or ASK) signal, $v_{out}$

Data in, $a(t)$

PSK

OOK

FSK

PHASE CHANGES

AMPLITUDE CHANGES

FREQUENCY CHANGES
Back Telemetry

- Using another wireless link to send data from implant to the external device.

MICS has been suggested for the wireless communication from implantable devices:
  - 402-405 MHz with 300 KHz
  - Data rate cannot be very high.
  - 10 dB with 10 mm tissue penetration
  - Can provide long range.
  - So far-Zarlink Company developed a chip. Size 7mmX 7 mm.

UWB in implants?

✓ For implants that require high data rate transmission.
  e.g. Implantable telemetry such as neural recording, electronic pill, body area network.

Disadvantages:
• Receiver is complex.
• Low transmission power.
• Very high tissue loss at high frequencies.

✓ How to overcome these challenges?
✓ Advantages:
  - High data rate
  - Transmitter is simple: less area, low power.
  - no effect on the other wireless systems in medical environment.
  - Electronic components are smaller at high frequencies.
UWB in implants?

- Use only Transmitter if possible.
- Send higher transmitter power from implant to external receiver according to the penetration depth.
  -41dBm is a regulation in the air.
Comparisons of Technologies with UWB

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<thead>
<tr>
<th>Model</th>
<th>Company</th>
<th>Frequen.</th>
<th>Data Rate</th>
<th>RF Power</th>
<th>Physical Dimension</th>
<th>Current</th>
<th>Tx</th>
<th>Rx</th>
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<tr>
<td>UWB</td>
<td>Ref1 <strong>&lt;br&gt;Ref2</strong>*</td>
<td>3.1 – 10.6 GHz</td>
<td>20 Mbps</td>
<td>-41 dBm</td>
<td>Very small</td>
<td>1.6mW 2mW</td>
<td>16 mA</td>
<td></td>
</tr>
<tr>
<td>Mica2 (MPR400)</td>
<td>Crossbow¹</td>
<td>868/916 MHz</td>
<td>38.4 kbps</td>
<td>-24 -+5 dBm</td>
<td>58 x 32 x 7 18 grams (board)</td>
<td>27 mA</td>
<td>10 mA</td>
<td></td>
</tr>
<tr>
<td>MicAz</td>
<td>Crossbow¹</td>
<td>2.4 GHz</td>
<td>250 kbps</td>
<td>-24 -0 dBm</td>
<td>58 x 32 x 7 18 grams (board)</td>
<td>17.4 mA</td>
<td>19.7 mA</td>
<td></td>
</tr>
<tr>
<td>Mica2DOT</td>
<td>Crossbow¹</td>
<td>433 MHz</td>
<td>38.4 kbps</td>
<td>-20+10 dBm</td>
<td>25X6 mm² 3 gram (board)</td>
<td>25 mA</td>
<td>8 mA</td>
<td></td>
</tr>
<tr>
<td>CC1010</td>
<td>TI²</td>
<td>300 to 1000 MHz</td>
<td>76.8 kbps</td>
<td>-20-+10 dBm</td>
<td>12X12 mm² (chip)</td>
<td>26.6 mA</td>
<td>11.9 mA</td>
<td></td>
</tr>
<tr>
<td>CC2400</td>
<td>TI²</td>
<td>2.4 GHz</td>
<td>1 Mbps</td>
<td>-25-0 dBm</td>
<td>7.1X7.1 mm² (chip)</td>
<td>19 mA</td>
<td>23 mA</td>
<td></td>
</tr>
<tr>
<td>MICS</td>
<td>Zarlink³ ¹ (ZL70250)</td>
<td>402-405, 433 MHz ISM</td>
<td>800 kbps</td>
<td>&lt; 0 dBm</td>
<td>7X7 mm² (chip)</td>
<td>5 mA, cont. TX / RX</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Comparison of hardware designs for wireless systems

* Reference (Ryckaert et al., 2007, IMEC UWB transmitter), **(Chae et al., 2008, Newcastle &UCSC), ***(Ryckaert et al., 2005, IMEC).

Multi-Channel Neural Signal Recording

Due to a large number of recording channels, naturally a huge amount of data should be transmitted.

Neural Recording

- Traditional recording methods are performed using biomedical instrumentation equipment that are generally stationary, bulky, limited to one or a few acquisition channels, and prone to excessive noise due to wiring.

- Simultaneous neural signal recording from many neurons has a wide range of applications:
  - study of the complex biological neural networks
  - brain controlled neural prostheses to treat spinal cord injuries by restoring limb movement

- The base band signal's date rate is $40K \times 16 \times 8 = 5.12\text{Mbps}$. (16 channel, 20Ksample/ channel/sec, 8 bit/sample).

- With using a UWB transmitter, all the sampled data from the 128 channels can be recorded and transmitted without any additional processing (8X16 Channel blocks.).


Wideband Telemetry Design

- Using UWB short pulses (wideband in frequency domain) for high data rate wireless telemetry

- Transmission range: 0m-10m

- Data rate: 10 Mbps up to 100 Mbps (current prototype)
  Future target: 500 Mbps
Pulse Generation Technique

\[ x(t) = \sum_{n = -\infty}^{\infty} g_T(t - nT_b) \]

\[ g(t - nT_b) = \begin{cases} 
A & nT_b < t \leq (nT_b + \tau) \\
0 & (nT_b + \tau) < t \leq (n+1)T_b 
\end{cases} \]

\[ x(t) = \frac{A \tau}{T_b} + \frac{2A \tau}{T_b} \sum_{k=1}^{\infty} \sin\left(\frac{\pi k \tau}{T_b}\right) \cos(kwt) \]

Pulse Generation Technique

\[ x(t) = \frac{A_1}{T_b} + \frac{2A_1}{T_b} \sum_{k=1}^{\infty} \sin\left(\frac{\pi k \tau}{T_b}\right) \cos(k\omega t) \]

- A rectangular-shaped data extends over an unlimited frequency band. When a high pass filter (HPF) is used, the UWB frequency from 3.1 GHz to 10.6 GHz frequency can be selected.
- It is also possible to use a band pass filter around a specific frequency.
UWB Signal Generation for Low Power Biomedical Circuits

\[ x(t) = \frac{2A \tau}{T_b} \sum_{k=n_1}^{n_2} \frac{\sin(\pi k \tau / T_b)}{(\pi k \tau / T_b)} \cos(k \omega t) \]

where \( \omega = 2\pi / T_b \), \( n_1 = \omega / \omega_1 \), \( n_2 = \omega / \omega_2 \), \( \omega_1 \) and \( \omega_2 \) are the lower and upper cutoff frequency of the bandpass signal.

Considering the fall and rise times, rise time adds an additional null to the circuit. Null due to rise/fall time occurs every \( 1/t_r \), null arises from the pulse width appears every \( (\tau + t_r) \) interval.
Transmitter Design

✓ The transmitter is designed in 0.35 µm CMOS technology

✓ Uni-directional data transfer

✓ Using UWB short pulses (wideband in frequency domain) for high data rate wireless telemetry
✓ Pulse shaping filter might be necessary to meet the FCC emission mask.
Modulation scheme
OOK-UWB, PPM_UWB and BPSK_UWB
Short Pulse Generation
National’s 0.35µm 4M2P CMOS process
The transmitter is designed in 0.35 µm CMOS technology and consumes 1.6mW with PPM modulation.
Pulse Generation Circuit

Spectrum of transmitted pulse.

Outputs time waveforms measured with oscilloscopes.
Pulse Generation Circuit

Generated PPM pulses with demodulated result
UWB Receiver Prototype

- Receiver is implemented using commercial off-the-shelf components
UWB Receiver Test Results

Received signal after 50 cm

Received signal after LNA stages
Ex-vivo Test Results

Wireless Endoscope (ePill)

A wireless endoscope monitoring system
# Current Trend in Electronic Pill

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(Thone, 2009)</td>
<td>640 X 480 pixels</td>
<td>MT9V013 (VGA)</td>
<td>144 MHz</td>
<td>2 Mbps</td>
<td>FSK</td>
<td>-18 dBm</td>
<td>Not finalized</td>
<td>3 V coin cell</td>
<td>NA</td>
</tr>
<tr>
<td>(Chen, 2009)</td>
<td>307,200 pixels</td>
<td>VGA, 0-2 fps</td>
<td>433 MHz</td>
<td>267kbps</td>
<td>FSK</td>
<td>NA</td>
<td>11.3X26.7</td>
<td>2X 1.5 V</td>
<td>8 mA (24 mW)</td>
</tr>
<tr>
<td>(Wang, 2008)</td>
<td>510X480 pixels</td>
<td>PO1200 CMOS</td>
<td>NA</td>
<td>NA</td>
<td>AM</td>
<td>High</td>
<td>10x190</td>
<td>3 V Wireless energy</td>
<td>125 mW</td>
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<tr>
<td>(Kfouri, 2007)</td>
<td>768 X 494 pixels</td>
<td>CCD ICX228AL</td>
<td>UHF</td>
<td>250kbps</td>
<td>--</td>
<td>NA</td>
<td>20X100</td>
<td>Li-ion</td>
<td>--</td>
</tr>
<tr>
<td>(Park, 2002)</td>
<td>510X492 pixels</td>
<td>OV7910 CMOS</td>
<td>315 MHz</td>
<td>NA</td>
<td>AM</td>
<td>NA</td>
<td>10 x 7 mm x mm</td>
<td>5 V</td>
<td>NA</td>
</tr>
<tr>
<td>Johannessen, 2006</td>
<td>pH and Temp.</td>
<td>Sensory: pH and Temp.</td>
<td>433 MHz</td>
<td>4 kbps</td>
<td>OOK</td>
<td>NA, 1m</td>
<td>12X36 mm, 8g</td>
<td>2X1.5 V SR48 Ag2O</td>
<td>15.5 mW</td>
</tr>
<tr>
<td>Valdastri, 2004</td>
<td>Multi-channel</td>
<td>Sensors</td>
<td>433 MHz</td>
<td>13 kbps</td>
<td>ASK</td>
<td>5.6 mW 5 m</td>
<td>27X19X19</td>
<td>3-V coin cell (CR1025)</td>
<td>--</td>
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<tr>
<td>Mackay, 1957</td>
<td>pH,temp. oxygen level</td>
<td>Sensors</td>
<td>100 kHz</td>
<td>--</td>
<td>FM</td>
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Antenna for ePill

![Diagram of an antenna for ePill with various components and measurements.]
Measurements

--UWB Transmission
--Using high gain receive antenna loss was 25 dB for 4 cm penetration
Wireless Endoscope (ePill)
S11 Measurement

- With the presence of tissue, antenna frequency shifted more than 2 GHz.
8-Channel Wearable ECG/EEG Monitoring System

Diagram of the 8-channel wearable ECG/EEG monitoring system, showing the flow from electrodes/sensors, through amplifiers, multiplexers, ADCs, microcontrollers, to UWB transmitters, and finally to UWB receivers and a computer via serial cable.
A multiple channel EEG/ECG monitoring system using low data rate UWB technology has been developed.

The system operates at 4 GHz central frequency and 1 GHz bandwidth.
• ECG sensor node and UWB transmitter using off shelf components.
• Multiple pulses per bit is transmitted.
UWB Based Sensor Nodes

Transmitter-2

Variable Oscillator

VDDB1

Buffer 1

VDDB2

Buffer 2

VDDC

XOR Gate

\[ t_p = \frac{C_L}{2VDD} \left( \frac{1}{k_p} + \frac{1}{k_n} \right) \]

- Variable UWB pulse generation, 300psec to 4nsec
UWB Transmission and Demodulation

Transmitted and Demodulated UWB signals
Continuous Vital Sign Monitoring Using UWB Band

a) ECG Signal from Oscilloscope

b) ECG Signal Corrupted with 50Hz Noise

c) FFT of corrupted ECG signal

d) ECG Signal after filtering

Frequency (Hz)

|Y(f)| (dB)

| Voltage (volts) |

Time (seconds)
Multi-Channel Monitoring Window
## What Multi-access Technique to Use for UWB-BAN?

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What Multi-access Technique to Use?

- UWB receiver consumes much more than UWB transmitter
- Can we Use transmitter-only approach?
- Characteristic of Transmit-only sensor node
  - Asynchronous transmission
  - No feedback, requires a collision avoidance and detection scheme

On body interference, due to collision from on body sensors

Off body interference, due to collision from external sensors

Users
Multi-access Technique for UWB-WBAN

On body collision avoidance

- Different transmission interval (T1 & T2)
- Maintain low duty cycle (Collision is proportional to duty cycle)
- Trade-off between processing gain and duty cycle

![Diagram showing sensor transmission slot with random asynchronous start times for Sensor 1 and Sensor 2, and their respective transmission intervals T1 and T2.]

Off body collision avoidance

- Different pulse rate for individual user (TP1 & TP2)
- Receiver on each user only accept single pulse rate

![Diagram showing different pulse rates TP1 and TP2 for User 1 and User 2.]

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Sensor Locations for UWB-WBAN

A WBAN Scenario with sensor locations

<table>
<thead>
<tr>
<th>Signal</th>
<th>Distance</th>
<th>$N_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) ECG</td>
<td>0.2 m</td>
<td>1</td>
</tr>
<tr>
<td>2) EEG</td>
<td>0.5 m</td>
<td>3</td>
</tr>
<tr>
<td>3) Heart rate</td>
<td>0.8 m</td>
<td>10</td>
</tr>
<tr>
<td>4) Blood Pressure</td>
<td>0.7 m</td>
<td>8</td>
</tr>
<tr>
<td>5) SPO2</td>
<td>0.4 m</td>
<td>2</td>
</tr>
<tr>
<td>6) Temp.</td>
<td>1 m</td>
<td>20</td>
</tr>
</tbody>
</table>
The Use of wireless in implantable electronics have been discussed.

Current needs:
- Long range power transmission
- High data rate
- Implant antenna technology
- Multi-access schemes.

UWB has been considered for neural recording, electronic pill and wireless body area network applications.

Low data rate UWB is used for medical monitoring of continuous signals.

Low-power UWB transmitters have been designed and analyzed for biomedical applications.

The impulse radio UWB has some advantages for wireless telemetry applications such as multi-channel neural recording systems, electronic pill and Wireless Body Area Network (WBAN).
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REFERENCES


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