Optimal Wireless Communication Method for Communication Inside the Human Body

Wouter den Bakker
University of Twente
P.O. Box 217, 7500AE Enschede
The Netherlands
w.a.bakker@student.utwente.nl

ABSTRACT
For various applications, for example medical implants, wireless communication inside the human body is required, which introduces unique requirements. Previous research has been done concerning several of those requirements, but there is no overview of all the requirements and which commonly used wireless communication methods fulfill those requirements. In this paper all the requirements are researched through a literature study. Those requirements include the size and energy usage of the implant, as well as the range, speed, absorption of the wireless communication method and the side effects of the wireless communication to the user. Furthermore this study focuses on finding the properties of commonly used wireless communication methods, including speed, range, penetration, safety and energy usage, which are compared to the requirements to find the optimal commonly used wireless communication method. This research will also list the ethical and social concerns caused by the wireless communication. The results show that applications that only send data when an event of interest happens, Bluetooth Smart is most suitable for applications with low data rate requirements and Bluetooth Classic for applications with high data rate requirements. For applications that require constant communication no suitable method is available due to limited battery power. For applications that require long range communication no suitable method is available either, due to required sending signal strengths that fall outside the safety limits.

Keywords

1. INTRODUCTION
There are multiple applications that require measurement of data inside the human body, for example monitoring a patients’ heart rate to prevent heart failure [7]. This raises the need to attach devices to people to monitor different conditions, or otherwise penetrate the skin to perform measurements. The attached devices usually limit the user's mobility and make monitoring obtrusive. Therefore sensors are sometimes inserted in the body, which communicate wirelessly with a monitoring device without hindering the user [26]. Examples of this include heart rate and blood monitors [7]. Also other implants, such as RFID chips for identification, may be inserted inside the human body. [25]

Wireless radio communication inside the human body comes with multiple difficulties that are not present with normal wireless communication. For example the wireless signals are absorbed far quicker than through air, greatly reducing the range of the signal [8, 31]. Furthermore, this causes the body to heat up, causing safety risks [1]. Another problem is the power supply. Either the power has to be supplied wirelessly, harvested from the human body or a limited amount of power in the form of a tiny battery has to be inserted along with the sensor. Other problems exist as well, such as it being possible to tap the communication, causing privacy issues.

Although several of those requirements have been researched, there is no overview for all those requirements and there is also no comparison between the wireless communication methods and the requirements. Therefore this study will find all the requirements and compare them to the commonly used wireless communication methods to find the optimal wireless communication method. In order to do so the following research questions will be addressed:

1. What are the requirements for wireless communication inside the human body?
   1. What are the general requirements?
   2. What are the application specific requirements?

2. Which commonly used wireless communication methods fulfill those requirements?

3. What are the ethical and social concerns regarding in-body wireless communication?

Due the fact a lot of information about the requirements is already available, a literature study will be done to find those requirements. This includes researching which applications make use of wireless communication inside the human body, in order to determine the application specific requirements. The applications will then be grouped, with applications that have similar requirements in the same group. This makes it easier to compare them later. After this a list of wireless communication methods will be made and for each requirement the properties of those communication methods will be researched and compared to the requirements. This yields the communication methods that are suitable for each group of applications. Lastly, the ethical and social concerns will be evaluated, after which the optimal wireless communication method for each group can be determined.

2. IMPLANT REQUIREMENTS
This section will list the requirements for the implants, which will be used to determine what wireless communication methods are suitable. The implants will then be divided into groups to...
make it easier to compare them. Only the requirements that are of interest for wireless communication are researched.

2.1 General Requirements

There are requirements that all implants need to meet, no matter what application. Those include the size of the implant, the energy limitations, the safety of using wireless communication and the penetration of the radio-waves.

2.1.1 Size

In order to be implanted easily as well as being unobtrusive the size of the implant should not exceed 1 cm³ [22]. The implant exists of: some sort of energy supply or harvester to supply power to the implant, a measuring sensor to do the actual measurements, an antenna and sensor to use this antenna for the wireless communication and some sort of container or isolation to ensure the safety of the user.

2.1.2 Energy

There are two ways to supply energy to the implant. The first one is by using a battery. However having to perform a surgery to replace a battery is unfeasible. Therefore the battery should supply power for the lifespan of the implant. Assuming the implant has a sphere shape, the volume can be calculated with $3/4 \pi r^3$. If no more than half of the available volume can be used for the battery, the volume of the battery is limited to $\pi/12$ cm³.

Assuming a high energy density battery is used, such as a lithium battery, which has an energy density of 4.32MJ/L [10], about 1,31 kJ energy can be stored. The other method is to harvest power from the surroundings. A currently used method is to harvest power from radio signals. Doing this inside the human body has two major drawbacks. The first drawback is that an antenna is needed to intercept the radio signals. However due to the size requirements the antenna has to be rather small and therefore only intercept a very limited amount of radio waves. The second drawback is that radio signals are quickly absorbed by the human body, so by the time they reach the implant a good amount of energy is already absorbed and can no longer be used. There are other methods in development that use for example body movement or chemical components in the human body to harvest energy [22, 22]. With this up to about 4 microwatt can be produced with current technology. This can be combined with a tiny rechargeable battery for applications that use more energy, but only during certain times.

2.1.3 Radio-Frequency Range and Side Effects

The most common way to transmit data wirelessly is using radio-waves. There are other ways to communicate of a short range, such as using the conductive properties of the body [12] or an electromagnetic link. However this is outside the scope of this paper, as it only researches the commonly used methods.

Therefore the possibilities for communication using radio-frequencies will be researched instead, more specifically the radio-frequencies from 3 kHz till 10 GHz. Radio-frequencies below 3 kHz are not used for normal wireless communication [29]. Furthermore radio-frequencies may harm the human body and there is relatively little research about the possible harmful effects of such low frequencies. Also radio-frequencies above 10 GHz are not commonly used for wireless communication [29]. Furthermore those frequencies introduce new harmful side effects and are absorbed even faster. A summary of the safety rules to prevent harmful side effects (using an uncontrolled environment over an average time of 6 minutes and f in MHz) can be found in Table 1-4.

### Table 1. Maximum allowed specific Absorption Rates [11, 14, 16-18]

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Whole body average (W/kg)</th>
<th>Localized: Head/Torso average over 1 g (1 cm³) tissue (W/kg)</th>
<th>Localized: Limbs average over 10 g (10 cm³) tissue (W/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 kHz – 10 GHz</td>
<td>0.08</td>
<td>1.6</td>
<td>4</td>
</tr>
</tbody>
</table>

### Table 2. Maximum allowed power density rates [11, 14, 16-18]

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Power density, S (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 MHz – 400 MHz</td>
<td>2</td>
</tr>
<tr>
<td>400 MHz – 2 GHz</td>
<td>0.200</td>
</tr>
<tr>
<td>2 GHz – 10 GHz</td>
<td>10</td>
</tr>
</tbody>
</table>

### Table 3. Maximum allowed electric field strength [11, 14, 16-18]

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Electric field strength: (V/m) (rms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 kHz – 1 MHz</td>
<td>280</td>
</tr>
<tr>
<td>1 MHz – 10 MHz</td>
<td>280/f</td>
</tr>
<tr>
<td>10 MHz – 300 MHz</td>
<td>28</td>
</tr>
<tr>
<td>300 MHz – 1.5 GHz</td>
<td>1.585f⁰.₅</td>
</tr>
<tr>
<td>1.5 GHz – 10 GHz</td>
<td>61.4</td>
</tr>
</tbody>
</table>

### Table 4. Maximum allowed magnetic field strength [11, 14, 16-18]

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Magnetic field strength: (A/m) (rms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 kHz – 1 MHz</td>
<td>2.19</td>
</tr>
<tr>
<td>1 MHz – 30 MHz</td>
<td>2.19/f</td>
</tr>
<tr>
<td>30 MHz – 300 MHz</td>
<td>0.073</td>
</tr>
<tr>
<td>300 MHz – 1.5 GHz</td>
<td>0.0042f⁰.₅</td>
</tr>
<tr>
<td>1.5 GHz – 10 GHz</td>
<td>0.163</td>
</tr>
</tbody>
</table>

2.1.4 Absorption

Radio waves lose power when they travel through materials. Through air they will lose power slowly, but especially through liquids they will lose power very rapidly. Considering the human body mainly exists of water, this may be a serious problem and should be considered too. To calculate how far the signal will travel 'penetration depth' is used. This is the depth at which the signal strength becomes 1/e of its original strength, not the depth at which the signal is completely gone. The penetration depth depends on the frequencies of the radio-waves and the tissue through which it travels. For comparison of various tissues at the frequency of 1 GHz see table 5. For comparison of the penetration depth of blood at various frequencies see table 6.
2.2 Application Specific Requirements

Aside from general requirements the different applications also have their own requirements. This includes the needed data rate, the type of communication (internal-internal or internal-external) and distance the radio-waves need to travel.

2.2.1 Applications

As this area is still heavily in development the number of applications that make use of wireless communication is limited. Nevertheless there are multiple applications that already make use of this and some of the requirements, for applications in development, can be guesses as well. Current applications that make use of this are heart rate measurement implants [7], identification implants [25], blood measurement implants [33], and device identifying implants [34]. Examples for applications that may become available in the (near) future are GPS trackers [25] and brain implants [6].

2.2.2 Data rate

Assuming a data sample is 4 bytes (a float, which allows for about 7.2 digits significance [13]) and no more than 50% overhead the following data rates are needed:

For heart rate and blood measurement this would be less than 1 kB/s, assuming no more than about 10 different types of data are measured and the rate at which it changes is less than 10 times per second. For identification and device identification this would be less than 100 B/s, assuming it only has to send an identification or security code. For a GPS tracker this would be 600 B/s [28]. Currently brain-computer interfaces use less than 20 kB/s [9, 27]. But they are still in development, so it is well possible that more useful data can be measured in the near future, requiring a higher data rate.

Assuming the data is only sent when it exceeds certain limits, so when an event of interests happens that an external device needs to know about, the actual requirements would be even lower.

2.2.3 Internal or External

Some communication may be between sensors inside the human body while other communication should only go to external devices. For heart rate and blood measurement this will be external only, because it is used for monitoring and if something happens an external device has to be notified. For identification and device identification it is external only, because the user or device needs to identify to external device. The same counts for GPS trackers, as some external device needs to know where the user is. For brain implants it may be useful to have multiple implants in different areas of the brain that send the collected data to a single implant before sending it to an external device, so internal communication may be needed, as well as external communication.

2.2.4 Distance

The distance the radio-waves have to travel mainly determine the strength of the signal needed. This includes both the distance it has to travel through the body and through the air to reach an external device. By using a cellphone as an in between device the distance it needs to travel through air can be greatly reduced. Only for GPS chips this would make no sense, as in that case it is better to use the GPS of the cellphone directly. GPS and identification chips can be inserted at the skin, heart rate measurement implants can be inserted at the edge of the heart, blood measurement implants should be inserted in the veins, device identification should be inserted at another implant (at different locations) and brain implants should be inserted in or on the surface of the brain. See table 7 for how far the signal has to travel through various tissues for average people. Unless noted otherwise this is to a nearby external receiver.

2.2.5 Groups

Applications have been grouped to make it easier to compare them later. Applications with similar requirements have been categorized in the same group, which resulted in the following groups:

1. Low data rate measurement group: This group requires a low data rate and needs to send data to external devices. It needs to send data through the human body

<table>
<thead>
<tr>
<th>Tissue</th>
<th>cm/penetration depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blood</td>
<td>2.6875</td>
</tr>
<tr>
<td>Brain White Matter</td>
<td>3.9494</td>
</tr>
<tr>
<td>Brain Grey Matter</td>
<td>5.3562</td>
</tr>
<tr>
<td>Cortical Bone</td>
<td>12.068</td>
</tr>
<tr>
<td>Dry Skin</td>
<td>3.8453</td>
</tr>
<tr>
<td>Fat</td>
<td>23.247</td>
</tr>
<tr>
<td>Muscle</td>
<td>4.068</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Frequency</th>
<th>cm/penetration depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 kHz</td>
<td>1 902.6</td>
</tr>
<tr>
<td>10 kHz</td>
<td>602.78</td>
</tr>
<tr>
<td>100 kHz</td>
<td>193.71</td>
</tr>
<tr>
<td>1 MHz</td>
<td>61.449</td>
</tr>
<tr>
<td>10 MHz</td>
<td>16.312</td>
</tr>
<tr>
<td>100 MHz</td>
<td>5.3723</td>
</tr>
<tr>
<td>1 GHz</td>
<td>2.6875</td>
</tr>
<tr>
<td>10 GHz</td>
<td>0.28013</td>
</tr>
</tbody>
</table>

As visible in table 6 the penetration depth quickly decreases at higher frequencies. Furthermore, table 5 shows that fat has relatively little influence on the penetration depth. This means that the signal strength does not have to be a lot higher for implants for overweight people.

Table 5. Penetration depth at 1 GHz [2, 5]

<table>
<thead>
<tr>
<th>Tissue</th>
<th>cm/penetration depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blood</td>
<td>2.6875</td>
</tr>
<tr>
<td>Brain White Matter</td>
<td>3.9494</td>
</tr>
<tr>
<td>Brain Grey Matter</td>
<td>5.3562</td>
</tr>
<tr>
<td>Cortical Bone</td>
<td>12.068</td>
</tr>
<tr>
<td>Dry Skin</td>
<td>3.8453</td>
</tr>
<tr>
<td>Fat</td>
<td>23.247</td>
</tr>
<tr>
<td>Muscle</td>
<td>4.068</td>
</tr>
</tbody>
</table>

Table 6. Penetration depth of blood [2]

<table>
<thead>
<tr>
<th>Frequency</th>
<th>cm/penetration depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 kHz</td>
<td>1 902.6</td>
</tr>
<tr>
<td>10 kHz</td>
<td>602.78</td>
</tr>
<tr>
<td>100 kHz</td>
<td>193.71</td>
</tr>
<tr>
<td>1 MHz</td>
<td>61.449</td>
</tr>
<tr>
<td>10 MHz</td>
<td>16.312</td>
</tr>
<tr>
<td>100 MHz</td>
<td>5.3723</td>
</tr>
<tr>
<td>1 GHz</td>
<td>2.6875</td>
</tr>
<tr>
<td>10 GHz</td>
<td>0.28013</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart rate measurement</td>
<td>5 cm (muscle) + 5 cm (fat) + 3 mm (skin) + 10 m (air)</td>
</tr>
<tr>
<td>Blood measurement</td>
<td>3 mm (blood) + 10 cm (muscle) + 5 cm (fat) + 3 mm (skin) + 10 m (air)</td>
</tr>
<tr>
<td>Identification</td>
<td>5 mm (muscle) + 3 mm (skin) + 10 cm (air)</td>
</tr>
<tr>
<td>Device identification</td>
<td>10 cm (muscle) + 5 cm (fat) + 3 mm (skin) + 10 cm (air)</td>
</tr>
<tr>
<td>GPS chip</td>
<td>5 mm (muscle) + 3 mm (skin) + 5 km (air)</td>
</tr>
<tr>
<td>Brain implant</td>
<td>6 cm (brain white matter) + 5 mm (brain gray matter) + 8 mm (cortical bone) + 3 mm (skin) + 10 m (air)</td>
</tr>
<tr>
<td>Brain implant (internal)</td>
<td>8 cm (brain white matter)</td>
</tr>
</tbody>
</table>

Table 7. Distance through tissues needed for various implants
for a semi-long range and a semi-short range outside that, even less if an in between device like a cellphone is used. This group includes heart rate measurement and blood measurement.

2. High data rate measurement group: This group requires a relatively high data rate, but none the less still a very low data rate compared to what modern wireless communication is capable of. It may need to communicate internally, to reduce the data needed to later send to an external device. A medium range inside the human body and a semi-short range outside that should are sufficient. This group includes brain implants.

3. Tracking group: This group requires a low data rate and needs to send its data to external devices, but also receive data. It needs to send the data a short range through the human body and a long range outside that. This group includes GPS chips.

4. Identification group: This group requires a very low data rate and needs to send its data to external devices as well as receive signals from external devices. Depending on what needs to be identified and where that object is, it may be needed to send it at a semi-long range or a very short range through the human body and a very short range outside the human body. This includes identification and device identification.

Although a lot more applications may come in the future, most applications that are being developed are of medical nature. These applications usually only measure data, meaning they fall in the low or high data rate measurement groups. Therefore the four groups represent a good amount of the applications that currently exist or are in development.

3. COMMUNICATION METHODS
This section will research what commonly used wireless communication methods exist and the characteristics of these methods. Those characteristics will then be compared to the requirements of the various implant groups, to find the optimal wireless communication method for each group.

Table 8. Wireless communication methods, their frequency and their data rate (upload)

<table>
<thead>
<tr>
<th>Name</th>
<th>Frequency</th>
<th>Data rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wifi</td>
<td>2.4 – 5 GHz</td>
<td>&gt;54 MB/s</td>
</tr>
<tr>
<td>Zigbee</td>
<td>868 MHz or 2.4 GHz</td>
<td>2.5 kB/s (low freq) 41 kB/s (high freq)</td>
</tr>
<tr>
<td>Bluetooth Smart</td>
<td>2.4 GHz</td>
<td>0.27 MB/s</td>
</tr>
<tr>
<td>Bluetooth Classic</td>
<td>2.4 GHz</td>
<td>&gt;1 MB/s</td>
</tr>
<tr>
<td>Ultra-wide Band</td>
<td>3.1-10.6 GHz</td>
<td>&gt;110 MB/s</td>
</tr>
<tr>
<td>GPRS (2G)</td>
<td>800 or 1900 MHz (region dependent)</td>
<td>&gt;17,8 kB/s</td>
</tr>
<tr>
<td>LTE (4G)</td>
<td>700-2600 MHz (region dependent)</td>
<td>&gt;50 MB/s</td>
</tr>
<tr>
<td>HSPA+ (3G)</td>
<td>700-2600 MHz (region dependent)</td>
<td>&gt;22 MB/s</td>
</tr>
<tr>
<td>MICS (frequency range)</td>
<td>402-405 MHz</td>
<td>0.6 MB/s [19]</td>
</tr>
</tbody>
</table>

3.1.1 Commonly used Methods
Table 8 gives a list of commonly used wireless communication methods that will be researched, their frequency and their data rate (upload). Medical Implant Communication Service (MICS) has been included as well, which is a frequency range rather than a communication method. This has been included because it is specifically developed for communication with implants and will be compared to the other communication methods as far as this is possible.

3.1.2 Data rate
As visible in table 8, the data rate for modern wireless communication methods is quite high compared to what is needed. GPRS has a low data rate, but is rather old. Bluetooth Smart and Zigbee have a lower data rate, but in exchange are more energy efficient. MICS is specifically used for medical implant communication and therefore has a lower bandwidth. Aside from the high data rate measurement group all wireless communication methods are more than fast enough. For the high data rate measurement group only the old and energy efficient communication methods, namely Bluetooth Smart, Zigbee and GPRS, may be to slow now or in the (near) future.

3.1.3 Distance
The distance from which radio-waves can receive and to where they can send depends on multiple factors. First of all the absorption of the radio-waves by traveling through the human body (and outside that, although air has almost no influence on the absorption). Furthermore the antenna used for sending and receiving. Also the power at which the radio-waves are sent and can be received determines the range. Last of all the noise from other signals may decrease the range. However, as it is impossible to adjust the noise in the implant itself this will not be researched.

The approximate absorption of the human body (in terms of penetration depth) for the groups at different frequencies can be found in table 9. This is communication to an external device. Internal communications occur at a shorter range and thus are absorbed less, meaning that the requirements in table 9 are the maximal requirements. For group 4 the absorption depends on what needs to be identified.

Table 9. Absorption in terms of penetration depth

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Group 1</th>
<th>Group 2</th>
<th>Group 3</th>
<th>Group 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>405 MHz</td>
<td>2,1</td>
<td>0,85</td>
<td>0,15</td>
<td>0,15-2,1</td>
</tr>
<tr>
<td>700 MHz</td>
<td>2,4</td>
<td>1,2</td>
<td>0,18</td>
<td>0,18-2,4</td>
</tr>
<tr>
<td>868 MHz</td>
<td>2,6</td>
<td>1,6</td>
<td>0,19</td>
<td>0,19-2,6</td>
</tr>
<tr>
<td>1.5 GHz</td>
<td>3,4</td>
<td>1,9</td>
<td>0,25</td>
<td>0,25-3,4</td>
</tr>
<tr>
<td>2.4 GHz</td>
<td>4,9</td>
<td>2,9</td>
<td>0,35</td>
<td>0,35-4,9</td>
</tr>
<tr>
<td>3.1 GHz</td>
<td>6,5</td>
<td>3,8</td>
<td>0,45</td>
<td>0,45-6,5</td>
</tr>
<tr>
<td>10 GHz</td>
<td>33</td>
<td>20</td>
<td>2,3</td>
<td>2,3-33</td>
</tr>
</tbody>
</table>

The power of radio signals is usually measured in dBm, where 3 dBm extra means about 2 times more power. For example 0 dBm equals 1 mW and 3 dBm equals 2 mW. For every 1 penetration depth the signal becomes e times weaker, so to convert penetration depth into dBm the following formula is needed:

dBm reduction = 10*log(\text{penetration depth})

The resulting dBm reduction can be found in table 10.
Furthermore the antenna may increase or reduce the range. This depends on the type and efficiency of the antenna. The efficiency of the antenna describes how well it converts power into radio-waves or back, while the type determines what is measured (electrical or magnetic field) and how directional the signal is. The signal for a dipole antenna, which sends the signals to almost all directions and is therefore suitable in most situations, has about 2.14 dBi gain for sending. That is: the signal is about 2.14 dBm stronger than an isotropic antenna, which sends the signal equally strong to all directions. According to other research, with the right antenna design, about 32 dBm reduction is to be expected for receiving signals [21, 30]. Depending on the location of the implant, location of the receiver, frequency, isolation of the antenna and other factors this may vary. However exact values for all the different parameters are not available, meaning the antenna gain cannot accurately be used to determine whether or not a certain communication method is more suitable than other methods.

Table 10. Absorption in terms of dBm

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Group 1</th>
<th>Group 2</th>
<th>Group 3</th>
<th>Group 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>405 MHz</td>
<td>9.1</td>
<td>3.7</td>
<td>0.65</td>
<td>0.65-3.7</td>
</tr>
<tr>
<td>700 MHz</td>
<td>10</td>
<td>5.2</td>
<td>0.78</td>
<td>0.78-5.2</td>
</tr>
<tr>
<td>868 MHz</td>
<td>11</td>
<td>6.9</td>
<td>0.83</td>
<td>0.83-6.9</td>
</tr>
<tr>
<td>1.5 GHz</td>
<td>15</td>
<td>8.3</td>
<td>1.1</td>
<td>1.1-8.3</td>
</tr>
<tr>
<td>2.4 GHz</td>
<td>21</td>
<td>13</td>
<td>1.5</td>
<td>1.5-13</td>
</tr>
<tr>
<td>3.1 GHz</td>
<td>28</td>
<td>17</td>
<td>2</td>
<td>2-17</td>
</tr>
<tr>
<td>10 GHz</td>
<td>143</td>
<td>87</td>
<td>10</td>
<td>10-87</td>
</tr>
</tbody>
</table>

Sending signals goes considerably better, considering the antenna has far less influence on that. The Ultra-wide Band will again be a problem. All short and medium range communication methods will not work for group 3. All short range communication methods at high frequencies may also be a problem for group 1, 2 and possibly 4, but may be overcome by using a cellphone as an in between receiver. Nevertheless the low frequencies perform a lot better in this area.

3.1.4 Energy usage

Depending on the data rate, the time it takes to set up a connection, the power at which the signal is send and the device the energy usage is different. Because the power needed to maintain a connection for the different wireless communication methods is far higher than the energy produced by a generator and will also quickly drain the battery, it is assumed no connection is maintained. As an estimate for the battery consumption it is assumed that only when something interesting happens a connection is set up and the data is sent at 1 kB/s for one minute, sending at least 1 packet per second. Depending on the application and the problem requirements for this may vary. It should be noted that every device implementing a certain wireless protocol (version) has a different power consumption with only limited data available about how well it performs under these conditions. Therefore the energy usage is no more than a rough estimate. As MICS is a frequency range the energy usage depends entirely on the implementation of the communication method using it. Therefore it has not been included. It is assumed that no more than half of the energy can be used for the wireless communication. Table 11 shows what this means for the various wireless communication methods.

Table 11. Energy usage of sending 1 kB data.

<table>
<thead>
<tr>
<th>Name</th>
<th>Energy Usage per send time</th>
<th>Times possible with 0.65 kJ battery</th>
<th>Times possible per year with 2 microwatt generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wifi</td>
<td>±5.4J [4]</td>
<td>120</td>
<td>12</td>
</tr>
<tr>
<td>Zigbee</td>
<td>±0.4J [23]</td>
<td>1625</td>
<td>158</td>
</tr>
<tr>
<td>Bluetooth Smart</td>
<td>±0.3J</td>
<td>2167</td>
<td>210</td>
</tr>
<tr>
<td>Bluetooth Classic</td>
<td>±0.4J [4]</td>
<td>1625</td>
<td>158</td>
</tr>
<tr>
<td>Ultra-wide Band</td>
<td>±6J [23]</td>
<td>108</td>
<td>11</td>
</tr>
<tr>
<td>GPRS (2G)</td>
<td>±7J [4]</td>
<td>93</td>
<td>9</td>
</tr>
<tr>
<td>HSPA+ (3G)</td>
<td>±8J [35]</td>
<td>81</td>
<td>8</td>
</tr>
</tbody>
</table>

Although it is possible to save some energy by using a weaker signal this will also greatly reduce the range. Furthermore the energy requirement will still be high, because a large amount of the energy is needed for processing rather than only sending the data.

It is clear that the wireless communication methods that are designed for a good energy efficiency, rather than a long range or a high data rate, are far more energy efficient and practical under the required circumstances. For group 1 this should be possible, assuming data is only send data when something of interest happens. For group 2 either there should be no internal communication or only at specific times, because there simply is...
not enough energy available to maintain a connection. This means that if something happens at one sensor it needs to wait quite some time before it can notify the other sensors. This may be a problem for certain applications. Therefore, it is properly better not to use internal communication and send the data to an external device directly. For group 3 this is not going to work. To track someone regular updates on the location of the user need to be sent. Considering this requires long range communication, which consumes a lot of energy this simply is not possible. For group 4 this may become a problem as it still needs to listen for incoming identification request or automatically identify itself on predefined intervals. Continuously listening for incoming identification requests is a problem and waiting till the implant identifies itself is no option either. Therefore either the implant somehow needs to know when to identify or radio-frequency induction, such as used with integrated circuit cards, should be used.

3.1.5 Safety

It depends on the size and shape of the antenna over what area the power is distributed. An antenna with a single point of origin that sends equally strong to all directions is used to estimate the limits. In practice the antenna will be slightly larger, better distributing the power, but also have the power more concentrated at certain areas.

According to the requirements no more than 1.6 W/kg averaged over 1 g (or 1 cm³) of tissue is allowed for the head and body. The area closest to the transmitter would absorb most energy. This would be a sphere with the radius of 6.2 mm, which has an equal volume. The percentage of energy absorbed can be calculated with:

\[
\text{Percentage absorbed} = 1 - \frac{1}{\text{penetration depth}}
\]

At 2.4 GHz 6.2mm muscle would absorb 23.8% of the energy that is passed through it [12]. The absorption for Ultra-Wide Band would be more, but that cannot be used anyway due to range limitations. Considering the allowed SAR is 1.6mW for 1g tissue and 23.8% absorption the sending signal may not be stronger than 1.6 mW/23.8% = 6.7 mW. This equals a signal strength of approximately 8 dBm. At 1 GHz this would result in about 11 dBm. At 2.4 GHz in white brain matter this would be 9 dBm. The medium and long range applications somewhat exceed this limit and may therefore be unsafe.

For the limbs this limit is 8 W/kg averaged over 10 g (or 10 cm³). This equals a sphere with a radius of 1.33 cm. At 2.4 GHz 1.33 cm muscle would absorb 44% of the signal. The allowed signal strength may therefore not be stronger than 80 mW/44% = 180 mW, or about 23 dBm. Therefore the limits should not be a problem for implants in non-critical areas.

**Table 12. Maximum transmitting power (in dBm)**

<table>
<thead>
<tr>
<th>Frequency</th>
<th>2mm isolation</th>
<th>3mm isolation</th>
<th>5mm isolation</th>
</tr>
</thead>
<tbody>
<tr>
<td>402</td>
<td>-10</td>
<td>-6.4</td>
<td>-2</td>
</tr>
<tr>
<td>800</td>
<td>-7</td>
<td>-3.4</td>
<td>1</td>
</tr>
<tr>
<td>868</td>
<td>-6.6</td>
<td>-3.1</td>
<td>1.3</td>
</tr>
<tr>
<td>1900</td>
<td>-3.1</td>
<td>0.4</td>
<td>4.9</td>
</tr>
<tr>
<td>2400+</td>
<td>-3</td>
<td>0.5</td>
<td>5</td>
</tr>
</tbody>
</table>

Furthermore there are limits for the power density. The power density of an isotropic antenna can be calculated as: (with \(4\pi r^2\) being the surface of a sphere)

\[
\text{Power density} = \frac{\text{transmitter power}}{4\pi r^2}
\]

With no distance from the transmitter this would result in infinite. Therefore there must be some isolation. The allowed transmitting power at certain frequencies and a certain amount of isolation is given in table 12.

This means that either a lot of isolation has to be applied (reducing the available space for the battery and measuring sensors) or a lower signal strength has to be applied.

Testing of a wireless router with a signal strength of 13 dBm [3] had a result of about 10 V/m electric field strength and 0.08 A/m magnetic field strength at a distance of 0mm [20]. However simulations show slightly higher values, reaching the limit for magnetic field strengths. Although depending on the antenna it may be more or less, this means that at a higher power output it may exceed the safety limitations.

It is clear that the maximum transmitting power is what mainly limits the signal strength. It is possible to send at reduced signal strength so those limits are not exceeded. This means that protocols that use a high signal strength can still be used. However this also means that the range is decreased, especially for protocols that have a high signal strength compared to the allowed signal strength.

3.1.6 Conclusion

Based on the above results a comparison between the wireless communication methods and the requirements has been made. This can be found in tables 13-16. (++ = very good, + = good, o = neutral, - = bad, -- = very bad, X = definitely will not work, ? = no data available)

**Table 13. Group 1: Low data rate measurement group**

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Data rate</th>
<th>Distance</th>
<th>Energy usage</th>
<th>Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wifi</td>
<td>++</td>
<td>o</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Zigbee</td>
<td>--</td>
<td>-</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Bluetooth Smart</td>
<td>++</td>
<td>-</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Bluetooth Classic</td>
<td>++</td>
<td>-</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Ultra-wide Band</td>
<td>++</td>
<td>X</td>
<td>--</td>
<td>-</td>
</tr>
<tr>
<td>GPRS (2G)</td>
<td>++</td>
<td>+</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>LTE (4G)</td>
<td>++</td>
<td>+</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>HSPA+ (3G)</td>
<td>++</td>
<td>+</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>MICS (frequency range)</td>
<td>++</td>
<td>+</td>
<td>?</td>
<td>-</td>
</tr>
</tbody>
</table>

**Table 14. Group 2: High data rate measurement group**

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Data rate</th>
<th>Distance</th>
<th>Energy usage</th>
<th>Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wifi</td>
<td>++</td>
<td>o</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Zigbee</td>
<td>--</td>
<td>-</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Bluetooth Smart</td>
<td>-</td>
<td>-</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Bluetooth Classic</td>
<td>o</td>
<td>-</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Ultra-wide Band</td>
<td>++</td>
<td>X</td>
<td>--</td>
<td>-</td>
</tr>
<tr>
<td>GPRS (2G)</td>
<td>++</td>
<td>+</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>LTE (4G)</td>
<td>++</td>
<td>+</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>HSPA+ (3G)</td>
<td>++</td>
<td>+</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>MICS (frequency range)</td>
<td>++</td>
<td>+</td>
<td>?</td>
<td>-</td>
</tr>
</tbody>
</table>
### 4. ETHICAL AND SOCIAL CONCERNS

In this section the ethical and social concerns that are the result of wireless communication will be researched in order to determine whether or not certain wireless communication methods can remove those concerns.

There are many social and ethical concerns with implants in general, for example the Islam forbids any modifications to the body [25]. However, at least some people are willing to use or already use implants. That means that an optimal communication method can be found. Considering those general concerns will not change what the optimal communication method is; these concerns fall outside the scope of this paper and therefore will not be researched.

#### 4.1 Concerns Overview

The main concern resulting from wireless communication is that everyone can receive the data sent. For example, it may be undesirable if other people are able to intercept the data sent from a brain implant and, with that, know what someone is thinking. Or people knowing someone has a certain disease, due to the information send from blood monitoring implants. For other implants, such as a heart rate monitor, this may be less of a problem. Furthermore even if the data cannot be read it may still be possible to track someone be using multiple receivers to determine where the signal is coming from. Assuming this is accurate enough it may even be possible to determine the location, and thus the function of the implant, at close range.

#### 4.2 Concerns Solutions

To prevent others from intercepting the data it can simply be encrypted. This however will increase the energy usage, due to additional processing being needed to encrypt the sending data and decrypt the receiving data. For identification this may be needed anyway, but for other applications this is an unnecessary extra step. Other ways to prevent people from reading the data or receiving the data in the first place is by limiting the range the data is sent as much as possible, for example using a cellphone as an in between receiver or reducing the sending signal strength. However the type of communication has no influence on this and therefore cannot be used to solve those concerns. Therefore, the optimal communication method does not change due to the social and ethical concerns.

#### 5. CONCLUSION

The implants have the following requirements:

- The size is limited to 1 cm³. The energy is limited to 1.3 kJ, or 4 microwatt. The safety limits can be found in Table 1-4. The data rates are below 100 kB/s; depending on the application even lower. Aside from some high data rate measurement applications, the communication is only to an external device. The penetration and range needed depends on the application.

The wireless communication methods have the following properties compared to the requirements:

- A high enough data rate, aside from the old and energy efficient communication methods for high data rate measurement applications. A rather limited range for sending for most applications and an even more limited range for receiving. Especially for high frequency and short range communication methods this is a problem. Aside from the energy efficient communication methods, which preform reasonable, the energy usage is too high to be practical for most applications. The power density is the limiting factor for the safety of the user, mainly reducing the sending strength for applications with a strong sending signal strength, such as long range communication methods.

Aside from privacy there are no ethical or social concerns caused by the wireless communication method and the communication method used has no influence on this.

This results in the following optimal communication methods:

- Bluetooth Smart would be optimal for applications that need to measure a limited amount of data (such as a heart rate or blood monitor), with Zigbee and Bluetooth Classic as reasonable alternatives.

- Both Bluetooth Smart and Bluetooth Classic would work for applications that measure relatively high amounts of data, such as brain implants.
For applications that require tracking people, for example with GPS, no non-intrusive wireless communications methods is currently working well, due to it needing too much energy and a too weak antenna that meets the size and safety requirements.

For applications for the identification of people or implants either a good method for notifying when to identify is needed, in which case Zigbee or Bluetooth Smart would be optimal, or some form of radio-frequency induction is needed, due to the limited amount of energy.

The frequency band of MICS may well be usable for communication with implants. Due to the good penetration of the low frequency it uses and the limited interference on that frequency it should be possible to have a long range without requiring too much energy. The frequency range is also large enough to provide the bandwidth needed for implants. The disadvantage is that the sending strength should be relatively low compared to other frequencies to prevent exceeding the maximum allowed transmitting power.

6. FUTURE WORK

Information on how exactly the antenna influences the sending and receiving strength in various mediums at the frequencies, as well as how it influences the electric and magnetic field strength is still lacking. A more accurate result on what communication method works best can be obtained with more detailed information in this area.

For most protocols there is no research about the energy usage at low data rates. Also each device using the protocol has different properties meaning only an (very) limited information available about those protocols. One of those protocols may be more preferable than the commonly used ones.

For optimal results it may be needed that a new protocol is designed for communication with implants that focuses on energy efficiency rather than a high data rate. It would be preferable to have a low frequency range, which currently is not used too much, to maximize range.

7. REFERENCES


