Implantable Radio Transmitters for Long Range Health Monitoring

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***Abstract*—Surveys and simulations are carried out on several implantable radio transmitters for health monitoring. The first half of this project focuses on gathering data on recent research in the area of Medical Implant Communication Systems (MICS), a standard aimed at improving communication distances to ~2 meters. Next we broaden our scope of coverage to include other bands outside the MICS band which achieve link distance over 2 meters by investigating Ultra Wide Band (UWB) systems and other potential long range radios. In addition we discuss various link performance parameters between several works to gain a better understanding of the system. Finally we run several simulations, using ADS Momentum to model the power gain between an implanted transmitter antenna (loop) in muscle tissue to a receiver antenna (dipole) in free space. Using data collected and the results from the simulations, a performance metric is formed for quantifying the power gain as a function of free space, tissue depth, and frequency.**

I. INTRODUCTION

The area of implantable radios, especially for long range health monitoring is fairly new, with only a handful of papers published to date. An older system that is employed involves inductive coupling to monitor patient health thereby limiting the transmitter range to just outside the body. The newly allocated band 402 MHz – 405 MHz for Medical Implant Communication System (MICS) [1] was created as an improvement on the older short range systems. With the new band also comes restrictions for operation; the Equivalent Isotropically Radiated Power (EIRP) of the devices operating in the MICS band are limited to 25 μW or -16 dBm in order to reduce interference with meteorological system (METAIDS) which also operates in the same frequency band. An additional protocol for MICS is "listen-before-transmit" operation which aims at reducing the amount of interference as a free channel should be found and used. In addition bandwidth for devices are also limited to 300kHz full or half duplex [2]. Ultra Wide Band (UWB) communication is another area that has been gaining attention after the FCC approval for commercial use in 2002 [**?**]. The key advantage to using UWB is the ability to generate large data rates through pulses in the tens to hundreds of MB/s regime at low power since it's been confined to a low radiated power density on the order of (-41 dBm/MHz between 0-960 MHz and 3.1 - 10.6 GHz) [3]. The trade-off for such low radiated power is very short range, which has limited the application of this technology (e.g. cochlear implants, Body Area Networks, vision prosthesis, etc). Achieving long distance communication has posed to be quite the challenge; [4] and [5] shows that it is possible to achieve link distances > 2 meters.

A. Goal

The main objective of this project is to apply what was learned outside the classroom to a practical application whereby one could develop better research skills to tackle future projects, which will rely heavily on the experience gained from this project and future ones.

II. LINK PERFORMANCE

Human tissue is a lossy medium, which means that signal propagation through tissue gets attenuated from point to point (i.e. tissue to surface) [6]. Depending on the depth of the transmitter, and the distance in free space, the amount of loss can be calculated. In [6], measurements are taken to determine the free space path to the patient under test:

$$PathLoss_{FreeSpace} = 20Log\left(\frac{\lambda}{4\pi d}\right) = 29dB$$

where$\lambda$is the wavelength (0.74 m for 405 MHz) and d is distance from base station. fading margin=18 dB to account for the additional signal attenuation:

$$TotalPathLoss = PathLoss_{FreeSpace} + fading\; margin$$

$$= 29dB + 18dB = 47dB$$

At microwave frequencies, z, h, y or ABCD parameters are difficult to measure (lead inductances, fringe capacitance), instead, scatter or s-parameters are solved for [7]. S-parameters are related to incident and reflected power, and are better suited for microwave frequencies than the previously mentioned parameters. Some properties of s-parameters that make them attractive to use are that, they can be measured on a device located at some distance from the measuring point and they can also be measured under impedance matching conditions, which is useful when making gain calculations. In addition to using s-parameters we define the return loss, R.L as the ratio of reflected power to incident power, expressed in negative dBs:

$$R.L. = -20log_{10}\left(\left|\frac{a}{b}\right|\right)$$

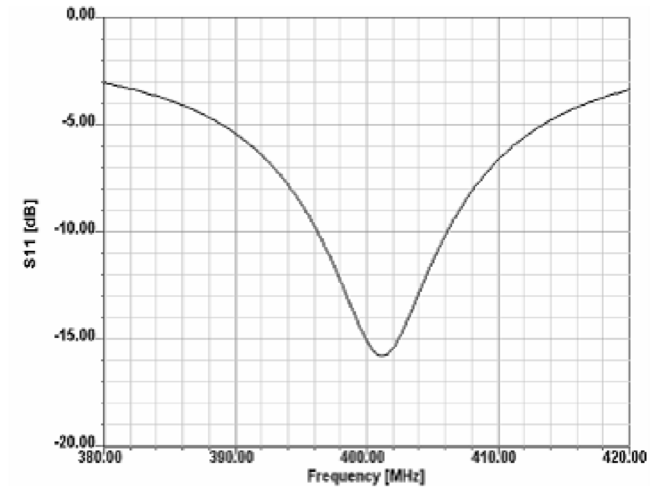

Fig. 1. Looped dipole antenna return loss

where *a* and *b* are the incident and reflected waves. The more negative the R.L, the better the impedance matching of the device. The general equation for the power gain is:

$$\frac{P_{load}}{P_{in}} = \frac{|S_{21}|^2\left(1-|\Gamma_{load}|^2\right)}{\left(1-|\Gamma_{in}|^2\right) * |1-S_{22}\Gamma_{load}|^2}$$

where $\Gamma = \frac{b}{a}$. We define simultaneous conjugate match as the condition when the output load results in an input impedance to the devices that is a conjugate match of the source; at the same time the source on the device results in an output impedance that is a conjugate match of the load. For simultaneous conjugate match, the maximum gain is then given as:

$$G_{tmax} = \left|\frac{S_{21}}{S_{12}}\right|\left(K - \sqrt{K^2-1}\right)$$

which is the ratio of power received by the Rx antenna to the power into the Tx antenna; K is the stability factor, at 1, G_tmax is equal to the maximum stable gain [8].

A. Parameter Definitions

In order to get a better sense for what constitutes an excellent or poor transmitter, we examine parameters that might aid in the evaluation process:

i. Antenna size: One of the most critical aspects in determining the link performance is antenna design. Several papers have been presented on what the optimum antenna design is given the limitations on size, and radiated power. For example, [6] presents a looped dipole antenna with a R.L. of ~ -15 dB in the range of 402-405 MHz Figure 1, and a dimension of 8.2 x 8.1 x 1 mm. Other types of antennas proposed for implanted radios include simple loop antennas [9], and even circumference antennas (in the case of a pace-maker) [6].

ii. Receiver sensitivity and bit error rate (BER): A great transmitter design should also be complemented with a receiver at the base station sensitive enough to the signal levels of the transmitter. Signal to noise ratio or SNR is defined as the ratio of the signal power to the noise power corrupting the signal. With this we then define Rx sensitivity as the minimum signal level that the system can detect with acceptable signal-to-noise ratio:

$$P_{in,min} = -174\frac{dBm}{Hz} + NF + 10\,logB + SNR_{min}$$

where $-174\frac{dBm}{Hz}$ is the absolute minimum sensitivity assuming conjugate matching at the input, the noise figure or $NF = \frac{SNR_{in}}{SNR_{out}}$, B is the bandwidth, and SNR_{min} is the minimum signal to noise ratio at the output.

- The sensitivity is in negative dBm, meaning the smaller the sensitivity value the lower the power requirement transmitter.
- Although we want a minimum SNR for better sensitivity, SNR must be greater than 1 for the receiver to detect a signal.
- Since thermal and other noise sources are spread across the entire frequency spectrum, having a lower bandwidth leads to better sensitivity.

Although not explicitly shown, the SNR also affects the BER (ratio of the number of received binary bits that have been altered due to noise and interference to total transferred bits). Improving the SNR lowers the BERs although by how much can be determined through measurements.

iii. Bandwidth, data rate and modulation scheme: For the MICS band, the maximum bandwidth allowed is 300 kHz, but we must also consider how it affects the other parameters. Higher bandwidth means more data rate, but also affects filtering accuracy. On the other hand it lessens the SNR requirement for the data rate. Different modulation schemes such as amplitude–shift keying modulations (ASK), frequency shift keying (FSK) and others, have been implemented in order to achieve higher data rate given the allotted bandwidth.

iv. Rx and Tx Power consumption: more care needs to be taken for the transmitter power consumption than for the receiver antenna, since it is more power constrained. Most implantable radios are meant to stay embedded for long periods of time, so if an implantable radio consumes on the order of mili-watts, it might not be so attractive, unless it is able to compensate with larger power supply or if it operates for shorter periods of time. The fact that the receiver is not as restricted as the transmitter allows some degree of freedom for the designer. The receiver can be made arbitrarily more complex in order to increase its sensitivity further than the conventional receivers. Moreover, the receiver is not as power constrained as the transmitter, which should also provide the necessary headroom needed for better performance.

v. Implant depth: as we shall see in the simulations section, implant depth is partly responsible for how much power is delivered to the Rx antenna.

B. Literature Comparisons

With the background and definitions needed, we move on to compare the different literature that were surveyed. Table I summarizes the first efforts at finding long range implantable antennas. Since most of the papers followed the MICS standard, the ranges of the transmitters were limited to just 2 meters. All of the papers discussed in the initial survey were some form of transceiver or another. This further complicates the design of the implantable radio thereby restricting the maximum range of the antenna. [10] although had the longest range in Table I, the internal device (AMIS 52000) is proprietary making it difficult to get details on the design of the internal device. In addition, FSK, is said to be a simpler implementation than QPSK and consumes less current, but has a higher BER, than QPSK [6]. Table 2 provides mostly non-MICS band standard radios with ranges > 2 meters. All the implantable devices on table 2 are implantable which makes it easier to estimate the efficiency of the transmitters with power consumption. Although both [4] and [5] are UWB transmitters, we see that [4] is much better able to achieve more than 2x the distance at a fraction of the power consumption by [5]. This shows that it is possible to achieve long range communication with implantable radio based on how much attention is given to the transmitter design. On another hand what [5] sacrifices in power it makes up for in data rate. Since the application for [5] is primarily recording in a closely monitored environment, power consumption is less of a concern.

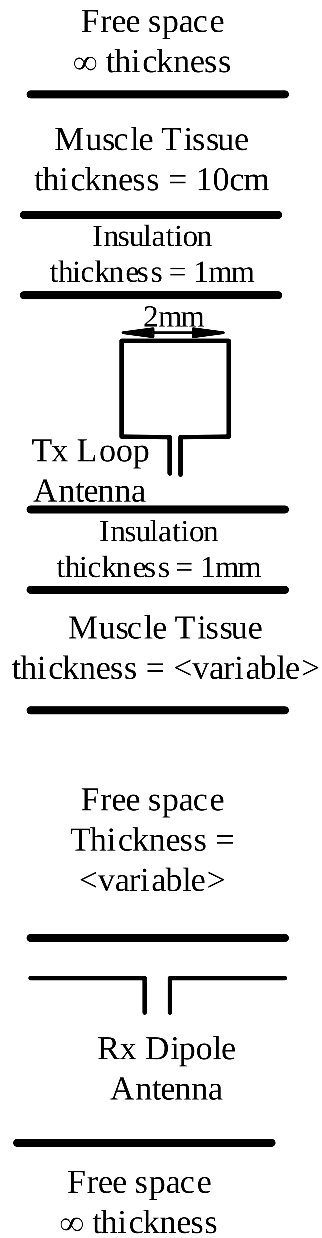

Fig. 2. Simulation setup

III. Project Results

A. Simulation

Figure 2 illustrates the simulation setup as follows: for the Tx antenna, a 2 mm diameter loop antenna(copper) was created surrounded by insulation in a muscle tissue layer, followed by free space, then a dipole antenna for Rx (copper). Both antennas were created with 50 Ω impedances and are axially aligned.

The permittivity of muscle at 403.5 MHz is 57.583 with a conductivity of 0.7972 $\frac{S}{m}$ [6], at 900 MHz, the complex permittivity of muscle is 55.032+18.832i with a conductivity of 0.92 $\frac{S}{m}$ [18]. Since tissue permittivity changes with frequency, two main sets of simulations were created, one at 403.5MHz, and the other at 900 MHz. In both cases the Tx loop antenna was fixed but the Rx dipole antenna size was changed for minimum return loss(Figure 3 and Figure 4). In the each set of simulations, two parameters were varied, tissue depth and the free space between the Rx antenna and the tissue surface. The biggest challenge in setting up the simulations was the time required to simulate larger free space was quadratic, limiting the amount of simulations.

Papers	[9]	[6]	[11]	[12]	[10]	[13]	[14]
Transceiver?	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Data Rate (kb/s)	120	300	200-800	See appendix	8	20	250
Rx Power Consumption (mW)	0.4	Not provided	>3(See appendix)	N/A	22.12	See appendix	0.49
Rx Sensitivity (dBm)	-93	-87	-96.02, -82.95@ 800 Kb/s	-96.02	-117 dBm @ 1 Kbps	N/A	80 $\mu V_r ms$
Tx Power Consumption (mW)	0.35	Not provided	>3	N/A	73.75	See appendix	0.4
Bit Error Rate percent	0.1	1-2	See appendix	See appendix	0.027	1-2 (Inferred)	1-2 (Inferred)
Process Technology (μm)	0.09	<0.5	0.18	0.18	0.5	0.18	0.18
Range (m)	2	1.64	>2	3.04	12	2	2
Verification	Ckt. sim.	Tissue emu.	Ckt. sim.	Tissue emu.	Ckt. sim.	Ckt. sim.	Tissue emu.
Carrier Frequency (MHz)	403.35	403.5	Not provided	403 (Inferred)	403.5 (AMIS)	N/A	402.1
Implant Depth (cm)	Ckt. sim.	Assume < 10 cm	Ckt. sim.	3-4	1	Ckt. sim.	Assume < 10 cm
Tx Antenna Dimension (cm)	2.3 diameter loop antenna	9.372 in length pacemaker antenna	Not provided	1.95 X 3.2 on a patch	Loop antenna, size not given	Not provided	Coil antenna, size not given
Modulation Scheme	OOK/MSK	QPSK/FSK	{2,4}FSK	{2,4}FSK	ASK/OOK Manchester /NRZ encoding	FSK	FSK

TABLE I
PERFORMANCE PARAMETERS FOR MICS BAND PAPERS

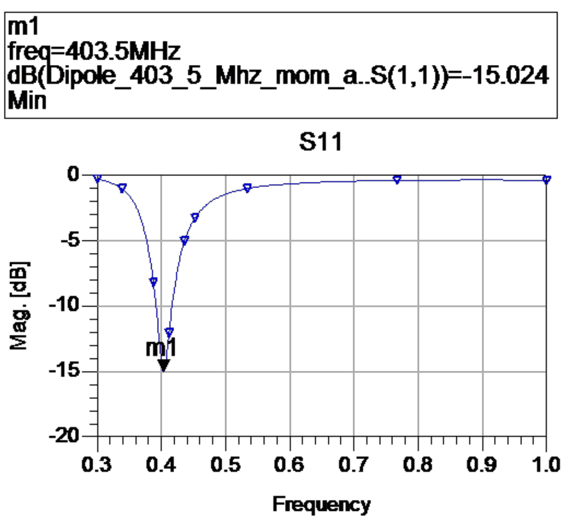

Fig. 3. Dipole antenna return loss at 403.5 MHz

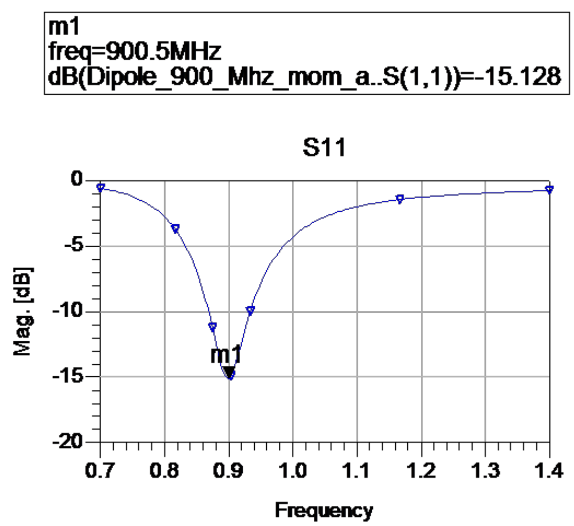

Fig. 4. Dipole antenna return loss at 900 MHz

Papers	[4]	**[15]Not Implantable**	[5]	[16]	[17]
Transceiver?	**No**	**Yes**	**No**	**No**	**No**
Data Rate (kb/s)	5120-10E3	0-16.7E3	14000	Comparable to 300	17500
Rx Power Consumption (mW)	Not applicable	Not provided	See appendix	Not applicable	Not applicable
Rx Sensitivity (dBm)	Not applicable	-99 to -45 (Worst Case)	-70 (Rx datasheet	Not applicable	Not applicable
Tx Power Consumption (mW)	0.792-0.802	0.096-0.718	10-21	2	3.5
Bit Error Rate	Not provided	1E-3 @ 100 kb/s	1E-4 - 1E-2	η=13.9 to 15%	< 1E-4
Process Technology (μm)	0.35	0.9	0.5	0.18	0.18
Range (m)	10	3	3.2-4	5	> 2
Verification	Ckt. sim	Ckt. sim	Water Phantom (water tank)	Ckt. sim	Ckt. sim
Carrier Frequency (MHz)	4000	Tunable	Not applicable to UWB	403.5	422
Implant Depth (cm)	Not reported, Ckt. sim	Not applicable	Not provided	Not implanted	Not provided
Tx Antenna Dimension (cm)	Not reported	Commercial antenna Omnidirect	Tapered triangle shaped 5.8 X 3.81	Not provided	Not provided
Modulation Scheme	OOK Manchester coded	DBSK	PAM or OOK	FSK	O-QPSK
Tx Power Out	Not reported	Not provided	Not provided	0.3 mW	-8 dBm to -15 dBm
Device Dimension	Assume < 1 cm^2	> 1 cm^2	420 μm X 420 μm	620*920 μm^2 in layout	Assume < 1 cm^2

TABLE II
PERFORMANCE PARAMETERS FOR RADIOS WITH > 2 METERS RANGE

The parameter of interest was the power gain,

$$G_{tmax} = \left| \frac{S_{21}}{S_{12}} \right|$$

. Using the results from ADS Momentum, Figure 5, 6, and 7 were constructed using MATLAB to show how the power gain changed with free space, tissue, and frequency. In all cases we see that the gain decays logarithmically off at distances >> 10 meters. In each case, a shallower implant depth led to an increase in the power gain. In addition we see that higher frequencies cause the gain to reduce much faster than for lower frequencies; this fact becomes clear at deeper depths. This is due to the fact that muscle conductivity increases for with frequency, 0.92 $\frac{S}{m}$ at 900 MHz vs 0.7972 $\frac{S}{m}$ at 403.5 MHz, thereby absorbing most of the signal generated by the loop antenna. Given these results, we see that the highest gain is obtained at shallower tissue depths, closer free space range and lower frequencies. On the other hand if one needs to operate at higher frequencies, shallow deeps are necessary to keep a comparable gain to the case with lower frequencies. An advantage to running at 900 MHz over 403.5 MHz would be the increase in bandwidth, although receiver sensitivity might suffer with the added demand for larger SNR.

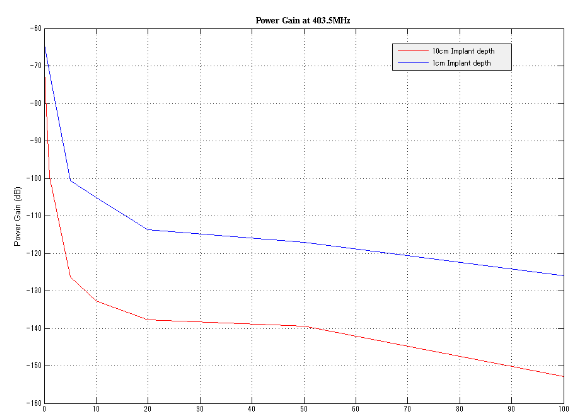

Fig. 5. Power gain at 403.5 MHz

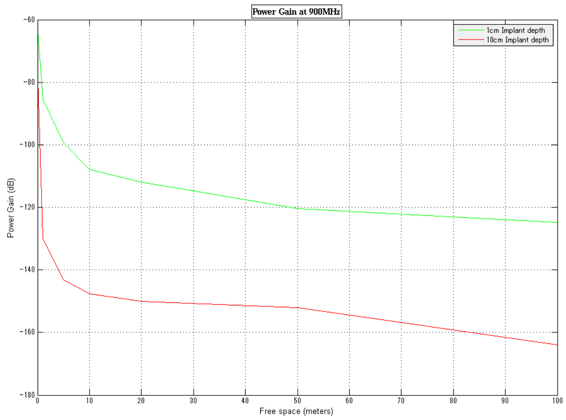

Fig. 6. Power gain at 900 MHz

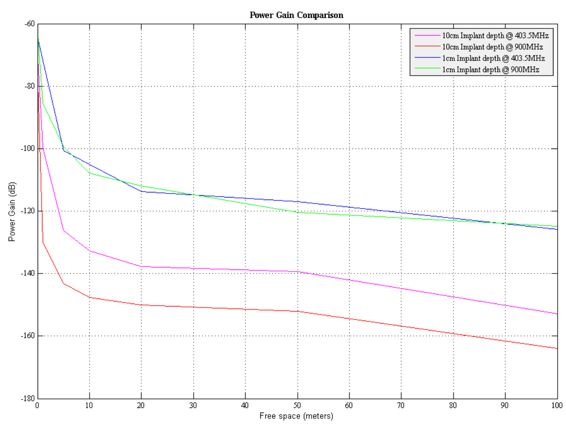

Fig. 7. Power gain comparison

B. Metric for Quantifying Power Gain

After trying several fitting models, we discover that the closest curve for the power gain is a function of the form:

$$Power\ Gain = c * log\Big(\frac{x}{1m}\Big) + d\ in\ dB$$

where we let x=free space, $c = -10\pm1$, determines how steep the knee of the curve is, and d<0, determines the shift of the curve in the vertical direction, and it is a function of frequency and implant depth. We define d as follows:

$$d = \left(80 + \frac{\sqrt{\frac{Frequency}{1MHz}}}{10} * \frac{Implant\ depth}{1cm}\right) dB$$

Given the number this information we can redefine the gain:

$$Power\ Gain = -\Big(10 * log\Big(\frac{free\ space}{1m}\Big) + d\Big)\ in\ dB$$

This equation gives a very good approximates of the Gain curve parameters of this project. As we can see, the link gain improves logarithmically with distance, and it also improves as a square root of frequency times the implant depth.

IV. Conclusion

In this project, several papers were presented on implantable radio as a way of gaining some intuition on how to best design the transmitter. In addition to the literature survey, simulations were run to confirm our understanding on what we discovered in the papers. Although the simulation environment contained just a few parts of the overall system (tissue and antenna), the results of the simulation proved invaluable in our understanding of the overall system; especially how the antennas affects link performance. With the equation derived from the results, it is easier to see the interaction with the other parameters not simulated such as sensitivity, and bit rate.

Given that most works on implantable radios are still in the sub 10 meter regime, there is still plenty of room for growth. As demonstrated in the simulations, the key to achieving good link performance lies in what frequency is used, and how deep the implant is in tissue, and how sensitive of a receiver can be built to complement the transmitter design.

Appendix A
Table I Notes:

[11]: sleep current = 250 nA. Tx and Rx current < 5.5 mA with supply voltage of 2.1-3.5 V The effective BER after FEC and CRC is better than $1.5 * 10^{-10}$, given a raw radio BER of 10^{-3}

[12]: The power limit for the wake-up transmitter is 100 mW. The power limit for the MICS transmission is 25 μW effective radiated power, taking into account of antenna gain. This 25 μW applies to the implant but only at the skin surface. Even if the raw power produced by the communication IC is in the order of 1 mW (0 dBm), losses through the body will typically reduce the power level to well below the 25 μW limit. In addition, the paper doesn't have a data rate; it measures the link by plotting the number of times ECC/CRC needed to be invoked to produce 100 good blocks of data. Power consumption is discussed in terms of ERP, not total consumption. The transceiver used is a Zarlink ZL70101 which is very similar to the transceiver in [19]. The effective BER after FEC and CRC is better than $1.5 * 10^{-10}$, given a raw radio BER of 10^{-3}

[13]: The power consumption of the transceiver PLL with a ring VCO are said to consume 800 μW, but this is a circuit simulation. The completed architecture can be found in Tekin, A., Yuce, M. R., and Liu, W. 2008. "Integrated VCOs for medical implant transceivers." VLSI Des. 2008, 4 (Jan. 2008), 1-10

[5]: Receiver used was ADL5513 by Analog Devices. For Single supply operation, 2.7 V to 5.5 V @ 31 mA

Appendix B
Major Points from the FCC Rules and Regulations on MICS Band

i. The monitoring system bandwidth measured at its 20 dB down points must be equal to or greater than the emission bandwidth of the intended transmission.

ii. Within 5 seconds prior to initiating a communications session, circuitry associated with a medical implant programmer/control transmitter must monitor the channel or channels the MICS system devices intend to occupy for a minimum of 10 milliseconds per channel.
iii. Based on use of an isotropic monitoring system antenna, the monitoring threshold power level must not be more than 10 logB(Hz) - 150 (dBm/Hz) + G(dBi) where B is the emission bandwidth of the MICS communication session transmitter having the widest emission and G is the medical implant programmer/control transmitter monitoring system antenna gain relative to an isotropic antenna.
iv. [95.633] says that power radiated in any 300 kHz bandwidth cannot exceed 25μW EIRP.
    a) The power measurement procedure are as follows from [95.639] (f) and (g). (f) is quoted below : Compliance of any MICS transmitter with the 25 microwatts EIRP limit may be determined by measuring the radiated field from the equipment under test at 3 meters and calculating the EIRP. The equivalent radiated field strength at 3 meters for 25 microwatts EIRP is 18.2 mV/meter when measured on an open area test site, or 9.1 mV/meter when measured on a test site equivalent to free space such as a fully anechoic test chamber.
v. Max bandwidth is 300 kHz. Full duplex or half duplex communications, just as long as the total amount of bandwidth utilized by all of the MICS channels in a session do not exceed 300 kHz.
    a) Emissions more than 250 kHz outside of the MICS band must be attenuated to a level no greater than table below:

Frequency (MHz)	Field Strength ($\mu V/m$)	Measurement distance (m)
30-88	100	3
88-216	150	3
216-960	200	3
960 and above	500	3

TABLE III
MICS BAND EMISSIONS RESTRICTION LEVELS

ACKNOWLEGMENT

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