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A 1000+ Channel Bionic Communication System

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Abstract— **The wireless electronic nervous system interface known as the Functional Electrical Stimulation-Battery Powered bion® System is being developed at the Alfred Mann Foundation. It contains a real-time propagated wave micro-powered multichannel communication system [1]. This system is designed to send bi-directional messages between an external Master Controller Unit (MCU), and each one of a group of injectable stimulator-sensor battery powered bion® implants (BPB). The system is capable of communicating in each direction about 90 times per second using a structure of 850 time slots within a repeating 11 millisecond time window. The system's total Time Division Multiple Access (TDMA) communication capability is about 77,000 two-way communications per second on a single 5MHz wide radio channel. Each time slot can be used by one BPB, or shared alternately by two or more BPBs. Each bidirectional communication consists of a 15 data bit message sent from the MCU sequentially to each BPB and 10 data bit message sent sequentially from each BPB to the MCU. Redundancy bits are included to provide error detection and correction.**

This communication system is designed to draw only a few microamps from the 3.6 volt, 3.0 mAHr Lithium Ion (LiIon) battery contained in each BPB, and the majority of the communications circuitry is contained within a 1.4 x 5 mm integrated circuit.

I. INTRODUCTION

THE extremely low power and subminiature size constraints of this communication system dominated the requirements and determined the approaches and tradeoffs taken for the system design, see Fig. 3. With thousands of neurons and hundreds of nerves and muscles, the total number of communication channels required for high spinal cord injured quadriplegics could easily run into hundreds or thousands of channels. One also has to consider that patients with these systems on the same frequency channel might be operating their systems in near proximity. The MCUs must coordinate communications in a manner transparent to the patient. Fig. 1 is a simplified diagram describing the communication channels for one patient.

II. SYSTEM DESCRIPTION

The transmitter power requirement: From experiments performed at the Mann Foundation it was determined that about 20 dB of signal loss occurs when a 500 MHz UHF radio signal penetrates beyond about four inches of body tissue [2]. Fig. 2 indicates the signal loss at different frequencies for sea water and for fresh water.

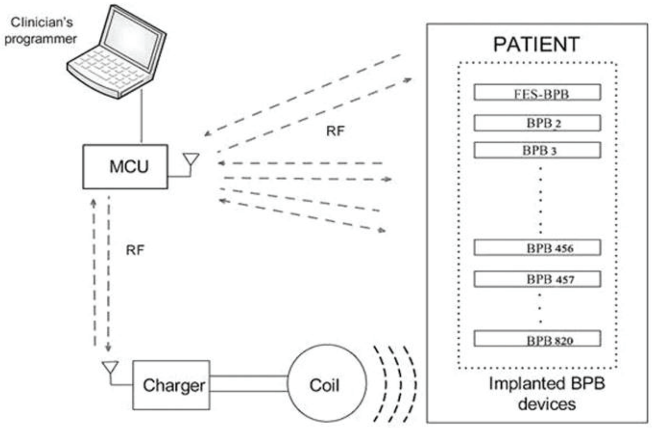

Fig. 1. FES-BPB System Block Diagram. Shown is the communication pathway between MCU and implanted devices and peripherals such as the battery charger.

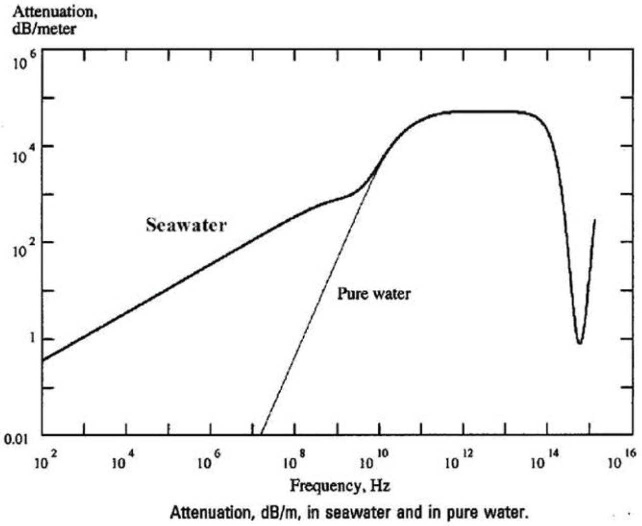

Fig. 2. Attenuation of RF energy in sea water and in pure water.

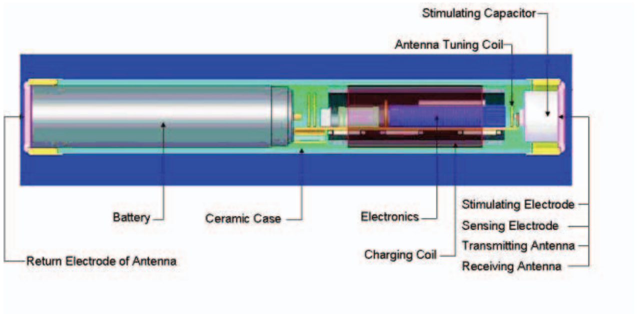

Fig. 3. BPB internal layout showing battery and electronics assembly.

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Sea water is approximately 9 grams NaCl per liter of water (i.e., normal saline). Body tissue is equivalent to about 1/5 normal saline. Based on this information and studies with phantoms containing simulated biological materials, it was determined that we would need about one milliwatt of effective radiated power to penetrate beyond four inches of body tissue, and still have a reliable signal [3]. This implies that we would need about 3 milliamps out of our 3 mAHr 3.6 volt battery to generate sufficient power to achieve the one milliwatt of effective radiated power. This is based on a system with 30% efficiency and includes processing overhead for the transmitter.

The receiver power requirement: From experimental measurements, it is clear that the signal at the BPB antenna will be somewhat below 10 microvolts at about four inches inside the body. The system low noise amplifier (LNA) that detects the microvolt level signal from the BPB receiver antenna needs to draw on the order of one milliamp from the 3 mAHr battery to have a sufficiently low signal-to-noise ratio to receive a reliable signal.

Battery power consideration: The 3.6 volt, 3.0 mAHr LiIon battery is made by Quallion Corporation specifically for use in the BPB. It has the unique property that if discharged to zero, it can be safely recharged without the dangerous accumulation of lithium metal. It is also designed to have a longer life of over 1000 full charge-discharge cycles. This is more than double the 500 cycle life normally specified for typical camcorder batteries. This battery, as with other typical LiIon cells, can have significant life extension if the depth of discharge is kept small. It is expected that an increase of about five times in life expectancy might occur if the depth of discharge can be kept at or below 25%. In this case, the 1000 full cycles becomes 5000 cycles, and with one cycle lasting four days, the 5000 cycles will take 20,000 days or about 50 years, though there are probably unknown chemical reactions that will prevent the cell from reaching this long lifetime. Based on the life expectancy assumption an attempt is being made to design a system that will keep the depth of discharge at no more than 25%, and the restrictions in quiescent current drain are specified for this possibility. Thirty microamps will discharge a 3mAHr cell in about four days, or 25% in one day. If we budget 15% for total quiescent current as a goal, then the total quiescent current allowed will be 4.5 uA.

The largest continuous quiescent current in the BPB is consumed by the 24.8 MHz crystal oscillator, which must always be running to provide a timebase for the BPB. The communications transceiver is the other main power consumer. The only way to design a communications transceiver where the transmitter and the receiver each draw 3 milliamps from the battery is to use a low duty cycle. If the duty cycle were 0.1% for the combined receiver and transmitter the total current drain will be 3 microamperes, which is within the targeted power budget. This necessitates a TDMA communication system with a 0.1% or less duty cycle. The present TDMA transceiver implementation and crystal oscillator together use about 4.2 uA.

Physiological considerations: Except for hearing, the fastest reflexes in the body operate at reaction times on the order of 50mSec. Based on this, it was decided that the maximum time for a two way communication between the MCU and a BPB should be on the order of 10 milliseconds, for about a five to one increase in communication transaction speed over the required minimum. The additional bandwidth would allow time for redundancy of critical commands, system level checking and diagnostics. Eleven milliseconds was selected as this communication frame time. The combined time for transmitter and receiver messages was therefore set at 11 microseconds (5.5 uS transmit and 5.5 uS receive). The total send and receive time is actually 13 microseconds to accommodate system settling times.

Coding Considerations: In an FES control system, each message from the MCU to the BPB contains one of the approximately 100 parameters that need to be programmed, and one of the approximately 250 values each parameter is to be programmed to. Thus a control word length of 15 bits was selected to be able to transmit the required parameters. For the response from the BPB to the MCU, 8 bits were chosen to allow read-back of the parameter values. Two additional dedicated bits are set aside; one to indicate that the received word was reliable, and the other to alert the MCU to a condition that requires attention within the BPB. The alert could be due to conditions such as the battery voltage falling too low, internal temperature getting too high, the charging field getting too strong, etc. When an alert is detected, the MCU must then query the BPB to find out what caused the alert.

Error detection/correction bits approximately equal in number to the data bits are included in the messages in both directions. For the MCU to BPB message, if too many errors are detected for the correction circuitry to handle, then the response message includes a reception error indication. Depending on the message, the MCU may resend the message. Commands critical to system operation can be checked by sending the message back for verification.

Modulation: To be more immune to amplitude variations and external noise, and yet still send data using the minimum bandwidth, it was decided to use quad-phase modulation (QPSK). Other more complex coding systems were considered, but power requirements made these more complex systems unadvisable.

Clock and phase stability: The crystal clock is powered by a low constant current (about 1.2 μA) that is sufficient to keep the oscillator operating with a small level of noise at zero cross over. Thus the average timing is accurate, but the phase time is not. When it is time to turn on the receiver, the current to the crystal oscillator is increased to provide accurate phase timing. The crystal oscillator frequency is then multiplied up to about 1.6 GHz to provide four stable quad phase timing pulses. When the received signal is detected, the error between the expected and actual baud timing is determined. This error is used to tune the crystal oscillator to cancel out this error. When working properly this error is reduced to several nanoseconds every time the correction is applied.

The header and automatic initialization: Upon activation of the BPB device, it immediately attempts to acquire the MCU signal. The MCU is identified by a frame header that includes an MCU identification number. The header identifies the MCU and the type of operation that is being implemented. BPB units are manufactured to wake-up looking for a super ID, where communication with a super MCU downloads a specific time-slot called the default. During fitting a BPB is assigned to a unique MCU belonging to the user. This new host MCU ID is then stored in the BPB and a new time-slot is specified in accordance with the use case for the BPB in question.

Patients together in a room all working in coordination on the same frequency channel: The MCU receiver is also used to detect transmissions from other MCUs. Due to the high power (1mW) radio signal generated by each MCU, MCUs can detect each other at a distance of about 100 meters. This will occur before the MCUs get within 3 meters of the implanted BPB's of the other MCU. In the event one or more MCUs are detected, the MCUs follow an established protocol in which the time slots being used to communicate to the BPBs are automatically shifted so that available slots are consumed and collisions with other adjacent systems are avoided, see Fig. 4. If too many systems are nearby, or if the systems contain a large number of BPBs which thus occupy much of the time frame, then this time slot shifting approach is not sufficient. In this instance BPBs can be shifted to communicate on a sub-slot basis where, for instance, a BPB will communicate every other frame, or every third frame, and so on.

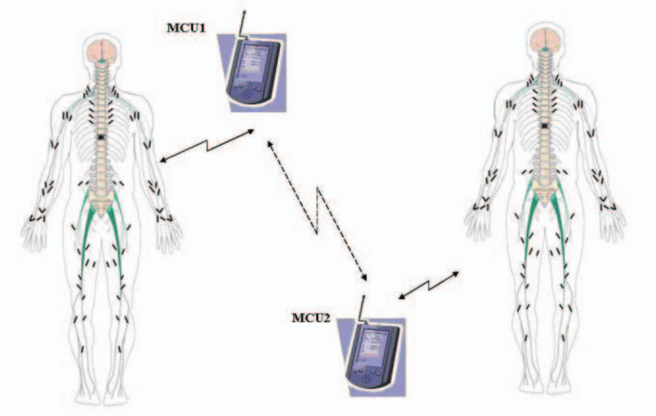

Fig. 4. MCUs communicating to facilitate sharing of time-slots between two users.

Additional radio frequencies: The communication system must share spectrum with other services. Most of the other services are 6 to 25 kHz wideband radio channels. The BPB communication system band width is about 5 MHz and can communicate effectively with up to about 10% of the band being used by other users. Since most users will have fewer than 20 BPB devices, the total time the system is on-air is approximately 3%. Therefore, we anticipate minimal interference to other users in this band. However, as the interference from other services in the band reduces the BPB communications reliability, the BPB system is capable of relocating to any one of three frequency bands used for BPB communications.

III. CONCLUSION

We anticipate having functional prototype systems by the end of the year.

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