WHITE PAPER

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Bio-patch Solutions for health and fitness: Why low-power design is imperative

Introduction

Bio-patch solutions are poised to revolutionize the health and fitness market and create new ways of providing healthcare both in clinical and remote settings. The wearable sensor enables patient safety and comfort in clinical settings and provides for long-term diagnostic monitoring while the individual participates in daily activities. For the athlete, the bio-patch provides an alternative to bands that suffer from noise artifacts such as motion and light. Given the unobtrusive and small form factor requirements of the bio-patch, optimizing power efficiency becomes highly critical in order to extend the lifetime of the system.

Bio-patch solutions are sensors worn on the body that enable continuous, as well as semi-continuous monitoring of physiological and cognitive parameters without tethering the patient or athlete to a wired hub. Regulation of physiological states can occur both from physical conditions or from cognitive functions associated with an individual's state of mind. Electro-dermal activity is a sensitive index of the nervous system activity. Nerve endings modulate physiological activity which may result, for example, in the stimulation of sweat glands. This stimulation leads to changes in skin conductivity which can be monitored via a physical sensor. The ability to monitor both the physiological and cognitive functions for an extended period of time outside of a clinical setting allows for innovative health management solutions.

The bio-patch sensor data is transmitted wirelessly to the gateway which provides for self-monitoring or remote monitoring by a healthcare professional. The disposable nature of the solution also helps meet patient safety requirements in hospital settings due to the one-time use of the bio-patch, which aids in preventing exposure to hospital infections associated with reuse of medical equipment. The bio-patch form factor also enables more intimate skin contact compared to other reusable wearable solutions providing for more accurate data collection. The bio-patch can also be placed in locations on the body that minimize noise artifacts associated with motion. The unobtrusive and small form factor requirements of the bio-patch solution drive a need for ultra-low power design considerations. Expected battery lifetimes range from 12-24 hours in clinical settings where the raw data is continuously transmitted to 7-10 days in a home-health or sports and fitness setting where the data is periodically transmitted. Those battery lifetimes can only be achieved by optimizing the energy efficiency of the entire system. A systems view of the bio-patch includes:

- RF interface
- Embedded processing requirements
- Sensor data collection
- Subsequent signal conditioning

We explore each of these system components and review methodologies for optimizing performance from a holistic view of the bio-patch taking into account a number of use conditions inside the medical and health and fitness space.

Bio-patch solutions

Bio-patches can be used to monitor a number of physiological parameters ranging from simple on-skin temperature measurements to more sophisticated electrocardiogram (ECG) type measurements. The same sensor solutions have been used to ascertain biological changes associated with an individual's state of mind. The modulation of the physiological state is achieved by the sympathetic and parasympathetic subdivisions of the autonomic nervous system. Increased sympathetic nervous system activity leads to increased heart rate, blood pressure, sweating and a redirection of blood from the intestinal section of the body toward skeletal muscles, lungs, heart and brain.

In **Table 1**, we list a number of sensor solutions with the corresponding parameters that can be quantitatively measured. The sensor solutions can be classified into two main categories consisting of physical sensors and chemical sensors. Physical sensors derive a measurable parameter due to a physical displacement or a change in the physical characteristics of the sensor. These include among many the piezoelectric sensor, photoelectric sensor and thermal sensors. Chemical sensors can be categorized as sensors that generate an electrical signal due to the chemical interaction with a biological component. Glucose sensors that are used to measure blood sugar levels from a correlation to interstitial fluids can be classified as chemical sensors.

Displacement	Ventricle size, muscle constriction, limb volume change, intestinal constriction
Velocity	Breath air flow, blood flow, heart rate, apex impulse
Pressure	Blood pressure, eye pressure, intracranial pressure, bladder pressure
Force	Cardiac muscle, occlusion force, bones, blood viscous force
Temperature	Mouth, recta, skin, viscera, eardrum
Biological Electricity	Cardiac, muscle, eye, stomach, nerve ending, skin
Chemical Components	K, Na, Cl, Ca, O2, CO2, NH2, H2, Li
Biological Components	Lactic acid, blood sugar, protein, cholesterin, antigen, hormone

Table 1. Common health and fitness sensor solutions

System Analysis

An example block diagram of the bio-patch solution is shown in **Figure 1**. The system consists of the physical sensor, the associated sensor signal conditioning, the signal processing unit, the data-logging component, the RF transmission unit and the overall power management component. Given the small and unobtrusive form factor of the bio-patch, maximizing the power efficiency of the system and thus optimizing the battery life-time of the solution becomes uniquely important. This involves an in-depth view of the entire solution. In most wireless systems, the RF component tends to drive the overall power efficiency of the solution if not optimized for the use case condition. The use case condition for the bio-patch breaks down into two main categories. In the first use case, the solution transmits the raw data to the hub where the data is processed and displayed. In this case, the signal conditioning algorithm resides on the hub. This use case is characterized by a large RF duty cycle where the RF component is on for a large part of the time thus drawing large amounts of current. In the second use case, the sensor signal conditioning algorithm resides on the sensor itself and only transmits the required information during predefined periods of time. In most cases, the sensor transmits only packets of information that correlate to a change in the physiological parameter being monitored. For this condition, the processing requirements along with the data-logging power efficiency need to be viewed closely.

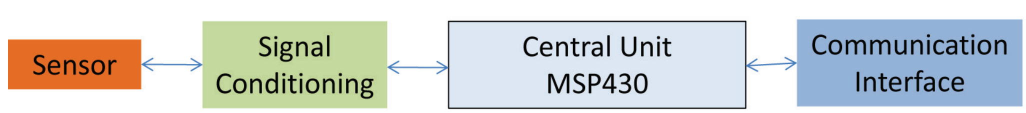

Figure 1. Example bio-patch block diagram

The process flow for data collection and subsequent transmission over RF is shown in **Figure 2**. The composite energy consumption for the system is given by the sum of the energy consumption for each of the major components in the system for the given RF protocol used for communication. The composite energy consumption for a typical bio-patch can be expressed as follows:

$$E_{composite} = E_{MCU\ total} + E_{sensor\ total} + E_{mem\ prog} + E_{mem\ erase} + E_{RF} \quad (1)$$

where

$$E_{RF} = E_{listen} + E_{t} + E_{r} + E_{sleep} \quad (2)$$

E_{MCU} total is the total energy consumption for the microcontroller (MCU) which consists of the sum of the active, idle and switching components, $E_{sensor\ total}$ is the sum of the power consumption for each of the sensors, $E_{mem\ prog}$ is the amount of energy required to carry out data logging and $E_{mem\ erase}$ is used to account for Flash block erase requirements associated with writing to this memory technology. E_{RF} is determined by the RF protocol used in the communication channel. For the Phy and MAC layers of an IEEE802.5.4 protocol, E_{listen} is the active listening energy, E_{t} is the energy for packet transmission, E_{r} is the receive energy and E_{sleep} is the radio sleep energy. The lifetime of the end node is dependent on the total energy consumed by the system and the battery capacity. The end node lifetime is determined as follows:

$$L_{node\ lifetime} = [\ C_{batt} \times V\ ]\ /\ E_{composit} \quad (3)$$

where C_{batt} is the battery capacity used in the system.

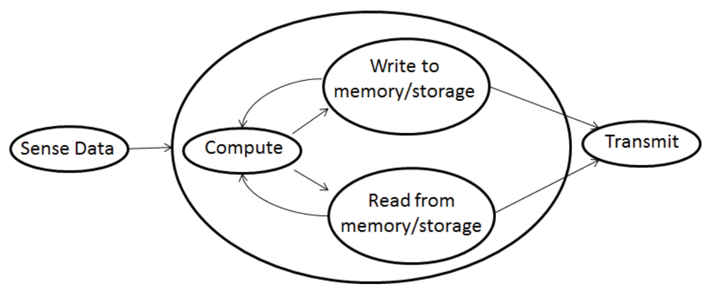

Figure 2. Process flow for data collection

One way to maximize the overall battery lifetime of the bio-patch solution is to minimize the RF duty cycle. As a comparison, we run an analysis using the device parameters shown in **Table 2**. Using equation 1, we calculate the lifetime of the system and look at the effect of varying the RF transmission time. As shown in equation 2, the overall RF duty cycle is determined by the amount of data transmitted or received and by the RF listening cycle. In **Figure 3**, we show that for this system the battery life-time of the system drops by 30 percent going from an RF duty cycle of .3 percent to .8 percent. At the highest RF duty cycle, the RF component of equation 1 becomes by far the largest component.

A number of RF standard protocols have emerged which have been designed to minimize the RF duty cycle by optimizing for occasional connections that allow for longer sleep times between connections and small data transfers. Bluetooth low energy (BLE) has been designed around this type of system. The latency of the solution is minimized by driving a need for the gateway to be continuously scanning for remote devices. Other communication solutions rely on a passive RF scheme to eliminate the RF component altogether. Near-field communication (NFC) provides for passive communication by enabling the end-point device, in this case, the bio-patch, to backscatter the RF wave generated by the gateway. Eliminating the RF component, translates to orders of magnitude increases in the overall battery lifetime of the bio-patch.

NFC fits within the transfer 'on demand' of the sensor collected data. While the NFC solution can be run with a battery such that the sensor continuously collects data, the device can also be run without a battery by scavenging the RF energy of the gateway. In this case, the bio-patch collects sensor data and subsequently transmits the data to the gateway 'on demand.' Both BLE and NFC have been adopted by major handset manufacturers, establishing an ecosystem that will enable the bio-patch market to expand even further into a wide variety of bio-patch applications.

Parameter	Value
I_{tx}	6.5 mA
I_{rx}	6.5 mA
I_{listen}	1mA
I_{sleep}	0.6 uA
I_{active} (MCU1)	120 uA/Mhz
I_{idle} (MCU1)	390 nA
I_{active} (MCU2)	235 uA/Mhz
I_{idle} (MCU2)	4 uA

Table 2. Device parameters used in the system analysis

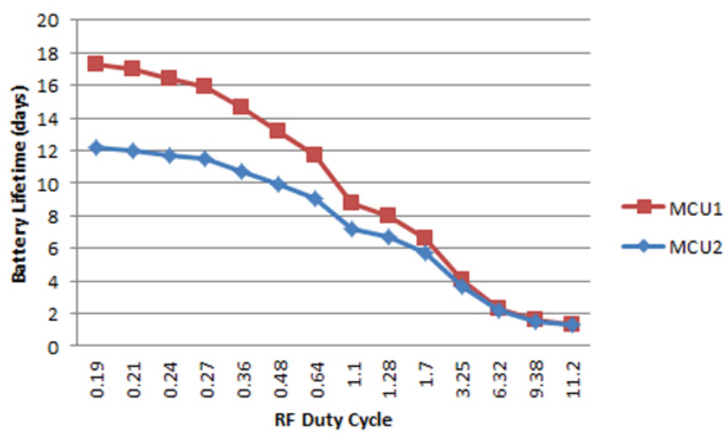

Figure 3. Simulated battery lifetime as a function of RF duty cycle.

At the lower RF duty cycles, the other components of the system have a more prominent role in the overall power efficiency. This is highlighted by the lower expected battery lifetime of the system with the MCU running at a higher active current. At the lower RF duty cycle of 0.19 percent, the expected battery lifetime of the system with MCU2 is approximately 30 percent lower compared to that of MCU1.

Data logging and battery life

We can extend the analysis to look at the impact of data logging on the overall battery lifetime of the system. In this case, we will take a look at the impact of two different non-volatile memory technologies. We will compare power efficiency associated with storing the collected sensor data using Flash versus ferroelectric random access memory (FRAM). FRAM is a non-volatile memory technology with similar behavior to dynamic random access memory (DRAM). Each individual bit can be accessed and unlike EEPROM or Flash, FRAM does not require a special sequence to write data, nor does it require a charge pump to achieve the higher programming voltages. FRAM programs at 1.5V versus the 10-14V of Flash or EEPROM. While Flash programming occurs through a tunneling mechanism, FRAM programming relies on a ferroelectric effect to induce polarization in a dipolar molecule. The ferroelectric effect occurs due to the electrical dipole formed by zirconium (Zr) and oxygen (O) atoms in the ceramic lead-zirkonate-titanate crystal (PZT) of the FRAM cell. The electric field causes a polarization hysteresis effect as it moves the Zi-atom within the PZT crystal with increasing field strength. The hysteresis occurs as a result of the interaction of this Zi-atom with the O-atoms. The Zi-atom is moved from one direction or the other by the polarity of the electric field. Unlike a magnetic hysteresis effect, the polarization hysteresis of the PZT molecule is not influenced by external magnetic fields. The Zi-atom atom will remain in place unless an electric field is applied and provides for non-volatility of the memory when power has been removed. This means that it wears down far less if at all for each memory operation, and consequently lasts more than 1 billion times longer than Flash. Finally, since FRAM is not written through a tunneling mechanism, it is up to 1,000 times more resistant to radiation such as gamma rays than Flash/EEPROM.

In addition, FRAM does not need a pre-erase cycle, and the molecule polarizes in one or two nanoseconds, so the write operation is about 1,000 times faster than the previously mentioned nonvolatile counterparts. Because the speed of FRAM is equivalent to embedded static RAM in many MCUs, in addition to its dynamic accessibility and non-volatility, it is what is commonly referred to as a "universal memory." This means it can function as the data memory or the program memory at any given time in its life. This gives designers the freedom to create embedded software that either relies heavily on data processing or does not rely at all on data processing, depending on their specific needs without worrying about the limitations of the MCU. No other embedded memory can claim this feature.

We consider the case where the collected sensor data is stored in non-volatile memory on either FRAM or Flash. To begin, we note that Flash is limited to approximately 10,000 write cycles due to its tunneling mechanism for data storage while FRAM write cycles are in the billions. This enables FRAM to be used in true data logging applications where data needs to be retrieved when system power is lost. To define the difference in the energy efficiency of the two memory technologies we use the device parameters listed in **Table 3** and calculate the battery lifetime of a bio-patch where the sensor data is logged. We account for the erase cycle of the Flash memory in the calculation. We also maintain the RF duty cycle of the system by limiting the amount of data that is transmitted assuming that the data is aggregated prior to transmission such that the overall packet of information is equivalent regardless of how much data is collected by the sensor. As can be seen in **Figure 4**, data-logging using FRAM does not impact the overall battery lifetime even for the case where the sensor is collecting 32 bytes of memory for the given sensor cycle. In contrast, data-logging to Flash results in a significant drop in the battery lifetime of the bio-patch up to 30 percent for 32 bytes of sensor-collected data.

Parameter	Value
$T_{program}$ FRAM	100e-9 sec
$I_{program}$ FRAM	.85 mA
$T_{program}$ Flash	100e-6 sec
$I_{program}$ Flash	2 mA
T_{erase}	20e-3 sec
I_{erase}	32 mA

Table 3. Memory data-logging parameters.

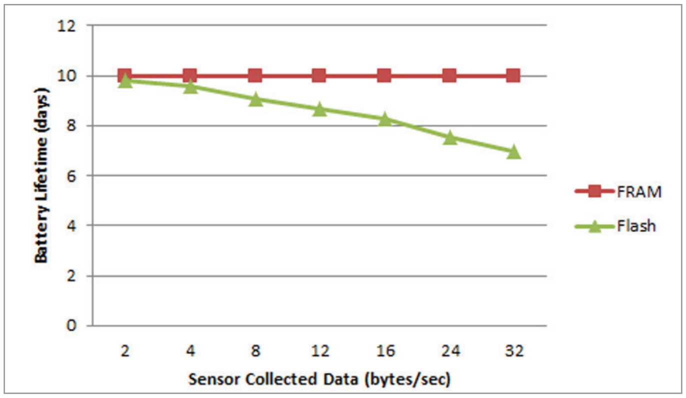

Figure 4. System battery lifetimes for aggregated data logging system solutions (FRAM vs. Flash).

The lower energy costs associated with data-logging on FRAM technology enable the use of in-network storage to reduce the overall communication requirements. In this case, the power consumption of in-network storage needs to be compared to the energy needs associated with the RF communications. As shown earlier, communication costs are quite high at the higher RF duty cycles and drive the lifetime of the system. By taking advantage of the lower energy costs associated with in-network storage and related computational costs of FRAM, the communications energy requirements can be significantly reduced. The overall reduction in communications energy costs can be achieved by enabling the sensor to carry out adaptive changes to its data collection based on the historical data collected over time. The sensor may choose to disregard data if it does not detect any significant changes based on the trends observed over a predefined sampling period. The system can build predictive time series models, taking advantage of the low computational energy requirements associated with the algorithm. These time-series models require a significant amount of historical data to build the required accuracy and can only be achieved with a low-energy consumption memory technology such as FRAM to take advantage of the local storage. The reduction in energy costs comes from a reduction of the amount of data that is transferred over RF.

The lower energy costs associated with FRAM also allow for aggregation of the sensor-collected data that rely on hash tables to perform duplicate packet suppression. These hash tables are typically too large to be carried out in RAM. FRAM-based data management schemes can be used to store these hash tables with low energy costs, thereby improving the performance of the system.

Signal chain and conditioning of the bio-patch

To finalize the signal chain of the bio-patch solution we look at the impact of the signal conditioning on the overall power efficiency calculation. The complexity drives from an understanding of the sensor signal being collected which is driven by the physical sensor itself. Driving the adaptive signal conditioning to the analog front end prior to the analog to digital conversion (ADC) reduces the computational requirements of the MCU and also minimizes the on time of the processor. As an example, we take a look at the sensor response of a typical electrocardiogram (ECG) signal shown in **Figure 5**. By identifying the period of time where you see a significant shift in the signal waveform you can optimize the sample rate of the ADC. Reducing the sample rate results in an overall improvement in the power efficiency of the system by minimizing the on time of the solution. Further improvements can be achieved by understanding transients that are superimposed on the actual signal of interest. In this case, removing the transients prior to the ADC reduces the requirements of the actual ADC. The superimposed transients drive a requirement for an ADC with a higher resolution had the transients been removed prior to sensing with the ADC. The power performance of a 14-bit successive approximation (SAR) ADC is significantly better compared to a 22-bit SAR ADC.

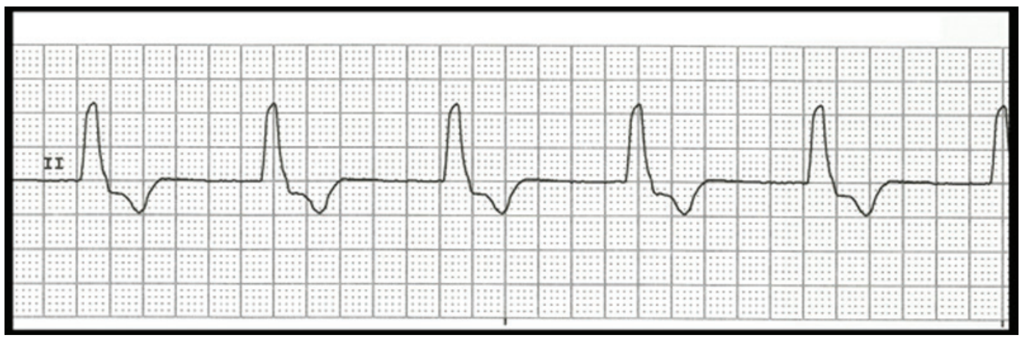

Figure 5. Typical ECG signal highlighting periods of significant change in the response.

Conclusion

The battery lifetime requirements of the various bio-patch solutions are dictated by the use- case condition. An optimization of the power efficiency is carried out by an understanding of the different system components that make up the total signal chain of the bio-patch solution in relation to the specific use case. For continuous monitoring solutions, we see that the RF component drives the overall system lifetime. In this case, optimizing the RF protocol to reduce the overhead associated with the communication link becomes highly critical. For semi-continuous or 'on-demand' solutions with lower RF duty cycles, the other components of the signal chain contribute a significant share of the complete power efficiency breakdown. Optimizing the low power performance of these parameters is crucial to achieving the battery lifetimes required by the use case.

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