AN1391

Introduction to the BodyCom Technology

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INTRODUCTION

The BodyCom system is a new short-range wireless connectivity technology that uses the capability of the human body to transport a few signals that provide intuitive, simple, and safe communication between two electronically compatible devices. Communication between BodyCom system devices occurs when they are within a few centimeters of the human body: a simple proximity or touch detection can establish a BodyCom system connection.

MICROCHIP SOLUTION

Traditional wireless remote access systems rely on a RF system, with a typical range of 400 to 900 MHz. While providing the convenience of remote control, these systems also require manual activation by the user and an additional level of security to prevent "sniffing" of the security codes during transmits. While these limitations are surmountable, they can be challenging for both the designer and the user. For example, when the user is trying to enter their house during a rain storm while holding a brief case and a bag of groceries.

BodyCom overcomes these limitations by using the user's body as the medium for data transmission. Data is capacitively coupled between the base and mobile units through the user's body using a low-frequency Amplitude Shift Key (ASK) format whenever the user and the base unit come in contact with each another. The user's touch also creates a simple capacitive touch detection to initiate the challenge and response sequence between the base and mobile units whenever the user is present.

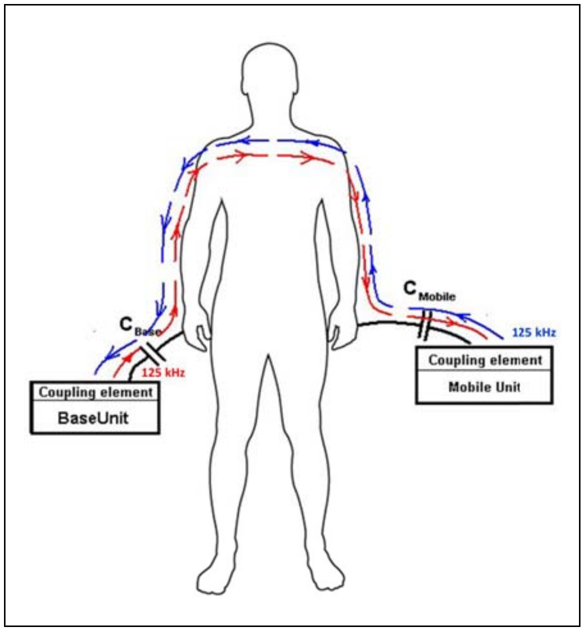
Due to the high permittivity of the human body at low frequencies, transmissions can be achieved with a simple, easily-designed system operating between 60 kHz to 10 MHz. The touch initiation system removes the need for manually triggering the sequence.

The BodyCom system provides an easy-to-use system that is secure to use and easy to design, layout and produce.

The BodyCom system was implemented with the following priorities:

- Very low consumption, especially for the mobile unit
- Fast-system response
- Stable and Robust communication with Fault detection
- Limited field of action (as little as a few centimeters) to allow an identification when the touch action takes place from whoever wears the mobile unit
- Low cost and complexity

FIGURE 1: BODYCOM SYSTEM WORKING PRINCIPLE



The signal transmission uses a low frequency near field communication channel between the human body, the base unit and the mobile unit (Figure 1). Because of this, the signals are more attenuated at low frequencies than at high frequencies, requiring the signals that are transmitted to have higher amplitude for lower frequencies. The mobile unit is a battery-powered portable device, and power consumption is a priority, while the base unit can deliver more power.

Another constraint in frequency choice is the result of the mobile unit's power consumption in Receive mode. This is a result of the limited low-power receiver circuits available on the market, which limit the receiving frequency to the 60-400 kHz range.

A frequency of 125 kHz has been chosen for the channel transmitted from the base unit and received by the mobile unit and vice-versa.

HOW BODYCOM WORKS

BodyCom is a RF System

BodyCom effectively turns the body into a low-frequency emitter. Coupling into the system allows charges to flow into the body, generating an electromagnetic field at the surface of the skin. Another unit will pick up the radiated energy and send a response back using the same method.

Any gathering of charges on a surface will create an electric field. The movements of these charges (current) create a magnetic field. A time-varying electric field will induce a magnetic field and vice-versa. Using Maxwell's Equations we can predict the EM-fields behavior.

EQUATION 1: MAXWELL'S EQUATIONS (DIFFERENTIAL FORM)

$$1.\quad \nabla \cdot \mathbf{D} = \rho_V$$

$$2.\quad \nabla \cdot \mathbf{B} = 0$$

$$3.\quad \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$4.\quad \nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}$$

EQUATION 2: MAXWELL'S EQUATIONS (INTEGRAL FORM)

$$1.\quad \oint\!\!\oint_S \mathbf{D} \cdot d\mathbf{S} = Q_{enc} = \text{Amount of Charge Within Surface } S$$

$$2.\quad \oint\!\!\oint_S \mathbf{B} \cdot d\mathbf{S} = 0$$

$$3.\quad \oint_L \mathbf{E} \cdot d\mathbf{L} = -\iint_S \frac{\partial \mathbf{B}}{\partial t} \cdot d\mathbf{S}$$

$$4.\quad \oint_L \mathbf{H} \cdot d\mathbf{L} = I_{enc} + \iint_S \frac{\partial \mathbf{D}}{\partial t} \cdot d\mathbf{S}$$

$$[I_{enc} = \iint_S \mathbf{J} \cdot d\mathbf{S}]$$

EQUATION 3: RELATIONSHIP BETWEEN D, E, B, H AND THE CURRENT DENSITY J

$$\mathbf{D} = \varepsilon \mathbf{E} \qquad \mathbf{B} = \mu \mathbf{H} \qquad \mathbf{J} = \sigma \mathbf{E}$$

In order to model this system we must consider the human body to be a gathering of point sources with a total charge Q. Using part one in Equation 2 in the integral form of Maxwell's Equations, we can solve for Q_{ENC}.This gives us the following (see Equation 4).

EQUATION 4: ELECTRIC FIELD AT DISTANCE R

$$E = \frac{Q_{enc}}{4\pi\varepsilon_0 R^2}$$

This tells us that the intensity of the electric field is proportional to the total charge given by Q=CV and inversely proportional to the distance-squared from the source. The voltage is directly related to the E-field by (see Equation 5):

EQUATION 5: ELECTRIC FIELD WITH RESPECT TO VOLTAGE

$$E = -\nabla V$$

This then gives us (see Equation 6):

EQUATION 6: VOLTAGE AT DISTANCE R

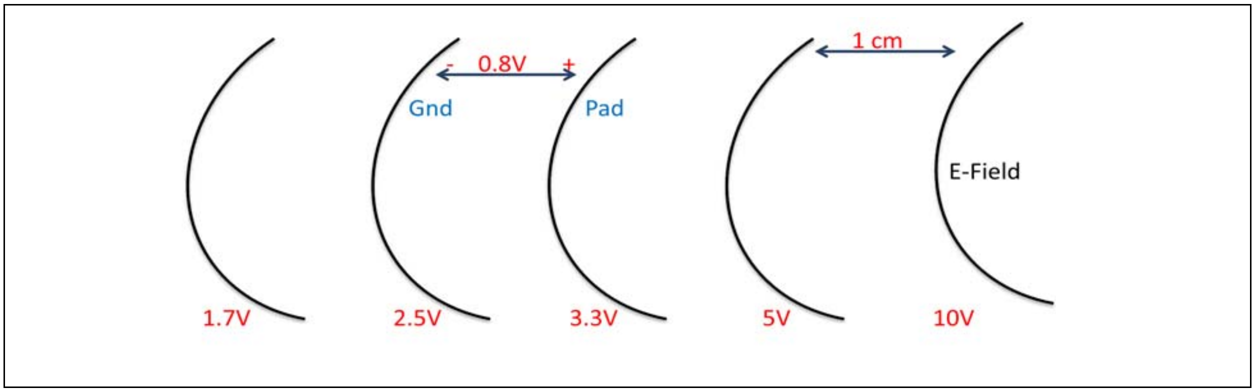
$$V = \frac{Q_{enc}}{4\pi\varepsilon_0 R}$$

DESIGN GUIDE

How to Pick up the E-Field Signal

Any conductor in an electric field will tend to equalize to the potential of the field around it. The following Figure 2 shows what would happen if two separate conductors are placed in the field. It creates voltage potential difference between the coupling pad and its common reference. The signal can be recovered by subtracting the two potentials.

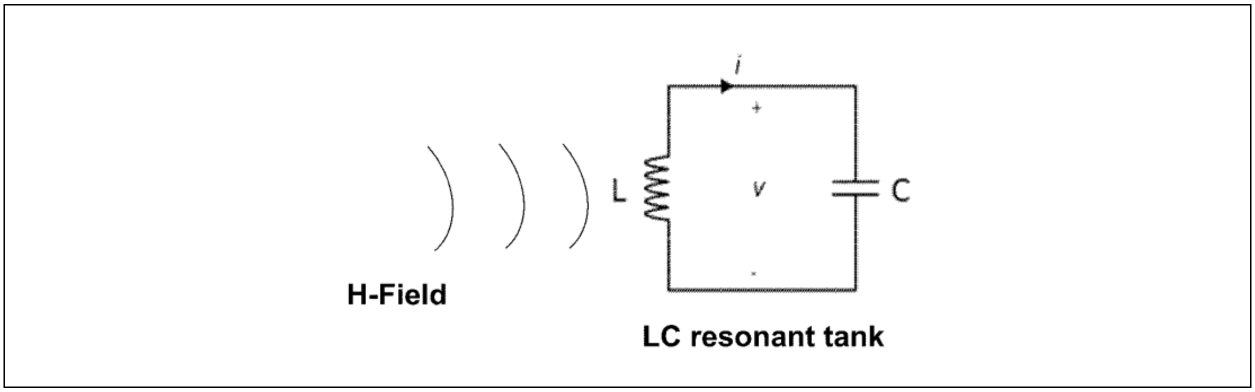
FIGURE 2: VOLTAGE ACROSS A BODYCOM PAD IN AN ELECTRIC FIELD



How to Pick up the H-Field Signal

Magnetic field energy will induce a current when it flows through a coil of wire (inductor). By building a parallel LC resonant tank tuned to the correct frequency, this energy can be captured (see Figure 3).

FIGURE 3: CURRENT INDUCED IN A LOOP BY A MAGNETIC FIELD



Bottom Line

BodyCom produces a time-varying signal in the near-field, meaning most of the EM signal is being generated by the source, as opposed to far-field wave propagation (radio waves). Signals in the near field are heavily influenced by the environment. This can cause problems if there are sources of noise or items of different electrical properties in the way (such as other conductors). Adding both a coupling pad and an RFID type coil will give a better chance at picking up the signal if there is something in the environment that is interfering with one of the fields.

Relationship to a Common Reference

The voltage generated by the source has a ground reference. The receiver needs to be coupled into this reference as closely as possible in order to recover the signal properly. Because the BodyCom system couples capacitively into the body, distance makes a big impact. The capacitance is given by Equation 7.

EQUATION 7: CAPACITANCE

$$C = \frac{\varepsilon A}{d}$$

And that ε is the permittivity of the material between the two plates; air in this case. Both a coupling pad and its reference pad are going to have some coupling into the body, depending on the distance of the pads and their respective sizes. If the coupling between both pads and the body is too close, the signal will be lost because they essentially get shorted together.

An ideal signal pad would have 100% coupling into the body and 0% coupling into the environment, while the reference (ground) pad would have 100% coupling into the environment and 0% coupling into the body, and the environment for the transmitting unit should be at the same potential as that of the receiving unit. The pad design is critical to maximizing their desired coupling.

Coupling and Ground Pad Design

There are two interesting application scenarios when designing the coupling pad sizes. The first is when there is direct-skin contact with the signal coupling pad, and the second is when there needs to be a distance between the pad and the skin.

If skin to pad contact is possible then the pad can be quite small. This is due to the system's ability to transfer energy to the body. Capacitance is much bigger when it is very close or even touching the skin directly. At this close range distance becomes the dominant term, and the actual area of the pad becomes much less important. In this case, the pad can be as small as the smallest part of the body touching it. The size of a fingertip, for example, would still provide enough capacitance to transfer enough energy to communicate successfully, provided your ground is big enough.

When skin contact is not possible, the area of the pad must increase to compensate for the much larger distance term. As the pad size increases, a greater distance can be achieved.

On the other hand, the ground pad must couple into the environment instead of the body. BodyCom works best in environments with some large central conductor such as a door frame or a metal desk. Having such large reference nearby will give both base and mobile units a common reference point to couple with. In most cases, the base unit will have a direct-wired connection to this common point via the wall supply used to power the system. This can eliminate a lot of pad design requirements on the base side because as long as it is connected to an external power source, the ground becomes earth ground and everything around that shares that reference. The mobile does not have this luxury and special care must be taken to ensure that it has the best coupling to the environment as possible.

BASE-TO-MOBILE TRANSMISSION

In a BodyCom system, the communication is initiated by the base unit. In order to start a communication when the system is coupled with the human body only, the PIC® MCU performs touch detection continuously.

When a touch is detected, the microcontroller stops touch detection and initiates a transmission that searches for the mobile unit. The generated sequence is applied through a driver to an LC circuit working in Resonant mode. This circuit is connected to a coupling pad that transfers the signal to the human body, effectively turning the body into a low-frequency RF emitter. In this way, the human body becomes an extension of the coupling element, allowing the transfer of the signal in the proximity of the mobile unit.

As previously mentioned, as the base unit can deliver more power to the transmitting channel, a low frequency (125 kHz) was chosen for the transmitting channel. This is possible because the base unit, being a fixed part of the system, can be powered externally or can have a bigger battery attached.

The signal generated by the base unit will be transmitted to the mobile unit, which is typically waiting in Signal mode (low-power consumption). The transmitted signal received will cause a wake-up of the mobile unit receiver.

MOBILE-TO-BASE RESPONSE

After the transmitted signal is received by the mobile unit, it decodes the data and, if a response is necessary, it will respond.

The mobile unit is also capacitively coupled with the human body; and can use the same method for transmitting back to the base unit. If the chosen mobile unit arrangement needs to use less power, a lower powered driver circuit can be implemented, but will lower the transmission distance.

The response is sent by the mobile unit using the 125 kHz transmitting channel; the signal is carried by the human body in the vicinity of the base unit and is applied through the coupling pad to the base unit receiving block. The output of the receiver is connected to the PIC microcontroller, and will receive the complete sequence and decode the incoming data.

BASE UNIT BLOCK DIAGRAM

The base unit should be able to perform the following functions:

- Touch/proximity detection
- Send challenge to the mobile units
- Receive and decode incoming data
- Simple communication/control interface for easy integration with other systems

FIGURE 4: BASE UNIT BLOCK DIAGRAM

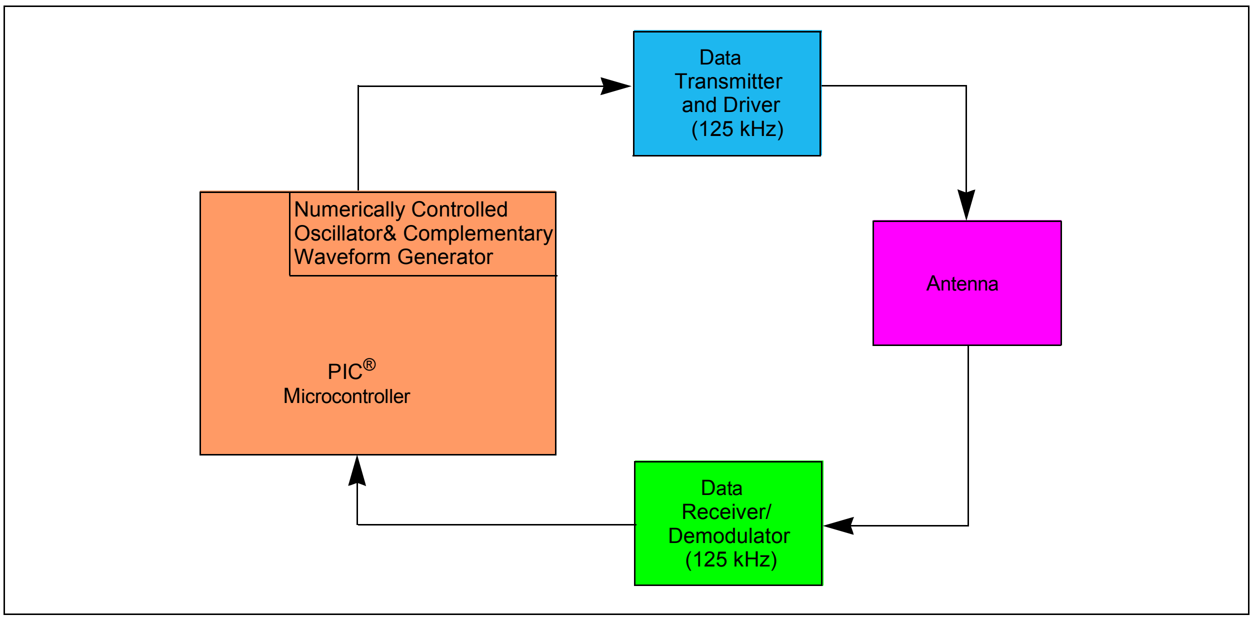


Figure 4 shows a block diagram for the base unit. It includes a complete receiver system, the transmission circuitry and a communication interface, all of which are managed by a PIC microcontroller.

The receiver module provides a robust and efficient demodulation/decoding circuitry implementation for compatible transponder signals. The microcontroller manages the complete transmission/receiving process, performing encoding/decoding and error detection. In addition, it supports implementation of a security algorithm for secure communication.

The transmitter module drives a coupling pad designed to support additional touch/proximity detection. A simple serial interface can be directly connected to other systems or microcontrollers to ensure easy integration and design flexibility.

TOUCH DETECTION

In a typical BodyCom system, communication between the base unit and the mobile unit is started when a touch/proximity event is detected. The base unit waits for this event and initiates the communication only when the user touches the pad or is in proximity of the coupling element (coupling/attenuation of the low frequency signal through the human body limits the range of the base unit to less than 1 cm).

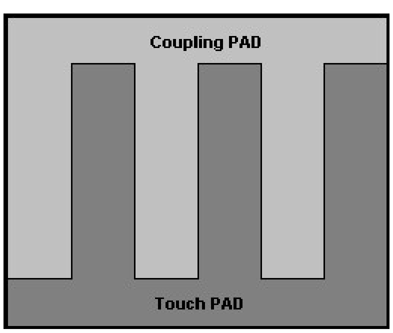
In our example, touch detection is achieved through the PIC microcontroller input using the CVD technique. The user may choose another method to do touch/ proximity detection for better performance of a custom design.

In a standard application, the coupling element and the touch pads are in close proximity. During the transmission, a high voltage is applied to the coupling element and affects touch detection. Because of this, touch detection should be stopped during this period.

The following configurations were used for the coupling element and the touch pad design:

1. Coupling Element and Touch PAD – Finger Style

FIGURE 5: COUPLING ELEMENT AND TOUCH PAD – FINGER STYLE

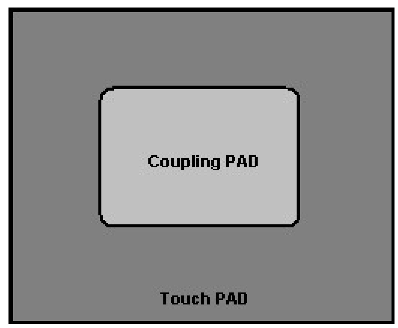


- The coupling capacitance between the coupling element and the touch pad is high, especially when the user touches the pad’s surface, which will cause a signal attenuation during the reception/transmission.
- The touch/proximity detection is easy and does not depend on the finger position on the pad area.
- The design needs two pads and wire connection between the pad area and the component area.

> **Note:** This design has good performance for applications where the coupling element/ touch pad need to be isolated (the user does not touch directly on the pad).

2. Coupling Element in the Center of the Touch/ Proximity Detection Area

FIGURE 6: COUPLING ELEMENT IN THE CENTER OF THE TOUCHING PAD



- The coupling capacitance between two pads is lower than with the previous solution; the user touches the coupling element directly, without touching the sensing pad. In this way, the attenuation of the incoming signal is minimum.
- The sensitivity of the receiver is increased compared to the previous solution, because the coupling with the touching pad is reduced.
- The design needs two pads and wire connection between the pad area and the component area.

> **Note:** The design is recommended for applications that require proximity detection.

3. The Pad is Shared by the Coupling Element and the Touch Circuitry

- The same copper pad is shared by the coupling element and the touching circuitry; only one wire is needed between the pad and the component area.
- The touch pad is connected directly to the LC circuit, where high voltage appears during the transmission. To avoid the possibility for high voltage to be applied directly to the microcontroller pins, the touch input should be connected to one of the ends of the LC oscillating circuit.
- The output capacitance of the driver and the input capacitance of the receiver appear directly in parallel with the capacitance of the pad, reducing the sensitivity of the touch sensing circuit (no proximity detection).

> **Note:** Because of the structure, a significant capacitance appears between the coupling element and the touch pad when this area is touched. To avoid false triggering of the system, it is recommended that the output of the driver be driven low during capacitive touch detection. The user may need to tune the CVD algorithm because of the big capacitance.

DATA PACKET STRUCTURE

The structure of the data packet used for communication should allow a robust communication between units. In Figure 7, the preamble sequence is required by the AS3933 to activate its circuitry. This sequence is followed by a timing filter (configurable in the software) that minimizes the false wake-up of the PIC microcontroller in order to minimize the power consumption of the entire circuit.

The communication begins with the first rising edge after the first wake-up filter event. This causes the PIC MCU to wake from Sleep and begin to decode the Manchester data.

FIGURE 7: RECEIVER STATE DIAGRAM FUNCTION BY DATA PACKET

Preamble	Wake-up Filter	Command Byte	Address	Length	Data[0..n-1]
4 ms ON, 0.5 ms OFF	2 Bytes	1 Byte	4 Bytes	1 Byte	n Bytes

MCP 2030	Wait for signal	Activate amplifier & data demodulator	Check filter time	Decode incoming data
PIC16LF1827	Sleep mode			Manchester Tx Active

The data packet is composed of two parts: one that is required by the hardware to work properly, and the other which is a data sequence.

The part required by the hardware has the following sequence:

- *Preamble time* – used by AS3933 internal circuitry to configure and activate its internal Automatic Gain Control (AGC) circuit (see AS3933 Data Sheet for detailed timing requirements)
- *Wake-up Filter* – User-configurable bytes used to tell the device that it can wake up and transmit data to the PIC MCU

The data sequence is a Manchester encoded data stream with the following packet format:

- *Command byte* – controls the action of the system
- *32-bit Address* – address of the mobile
- *Length byte* – contains the length of the data packet
- *Data[0..n-1]* – data packet

NUMERICALLY CONTROLLED OSCILLATOR (NCO) AND COMPLEMENTARY WAVEFORM GENERATOR (CWG)

For easy modulation of the data packet, with minimum usage of the PIC MCU processing power, the BodyCom system uses microcontrollers with an on-chip Numerically Controlled Oscillator (NCO) and Complementary Waveform Generator (CWG) (PIC16F/LF150x family).

The Numerically Controlled Oscillator (NCO) is a peripheral that allows the user to divide down the clock source frequency. It is capable of reducing the input frequency from its max. value to zero linearly with 16 bits of resolution. This can be used to create a very accurate 125 kHz signal, which can then be adjusted to maximize the output to compensate for variations in component tolerance levels.

The Complementary Waveform Generator (CWG) can take any input signal and output both the original signal and its complement signal. It has features like automatic shutdown, and rise and fall dead-band control.

The BodyCom system uses the NCO to generate the 125 kHz carrier frequency, which is then modulated with the desired signal using the NCO's software enable bit. It is then fed internally into the CWG. The CWG will output the modulated signal and its complement to the transmit circuitry. By using those hardware resources, the PIC MCU processing power is reduced to minimum.

According to the AS3933 requirements, the allowed baud rates are between 100 Hz and 10 kHz. A higher possible baud rate in this range is recommended, because it reduces the active time required by the PIC MCU during reception and transmission, reduces power consumption, and increases battery life (especially for the mobile unit).

BASE TRANSMITTER

On a typical BodyCom system, the base unit initiates communication with the mobile unit. The microcontroller delivers a square-shaped voltage that is applied to a driver working with a series resonant LC circuit. Due to the full-bridge configuration of the drivers, the peak-to-peak output voltage, V_{pkpk}, is approximately double the power supply, corresponding to an RMS voltage about power supply:

EQUATION 8: OUTPUT VOLTAGE

$$V_{PKPK} \sim 2 * V_{DD}$$
$$V_{rms} = V_{LC} = 50\% * V_{PKPK} \sim V_{DD}$$

The current flowing through the coupling pad is sine shaped, and the peak and RMS values are approximately:

EQUATION 9: CURRENT THROUGH THE COUPLING PAD

$$I_{ant} = \frac{4}{\pi} * \frac{V_{LC}}{R_{LC}}$$

In general, the higher the Q, the higher the power output for a particular LC circuit.

EQUATION 10: POWER

$$P = \frac{V_{rms}^2}{R}$$

Unfortunately, too high a Q may conflict with the band-pass characteristics of the transmitter, and the increased ringing could create problems in the protocol bit timing. Those reasons and the bandwidth required for transmission of the data limit the quality factor of the LC circuit.

BASE UNIT LC DRIVER GUIDELINES

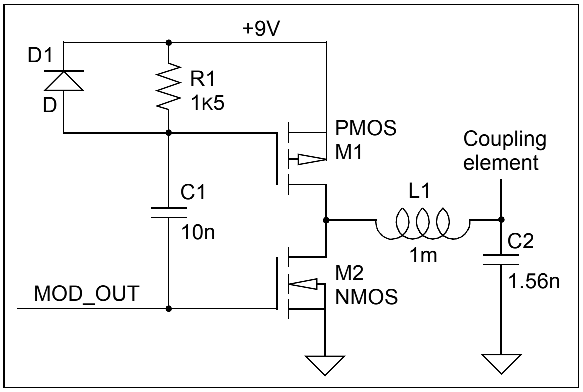
When a specific driver configuration is used for the BodyCom system, the following criteria needs to be considered for this circuit:

- Be able to drive the LC circuit in Resonant mode at 125 kHz, with smooth and fast transitions from on-to-off state
- Have low output resistance in Transmitting mode
- Have low-power consumption during reception or Idle state

The following configurations were used for the LC driver:

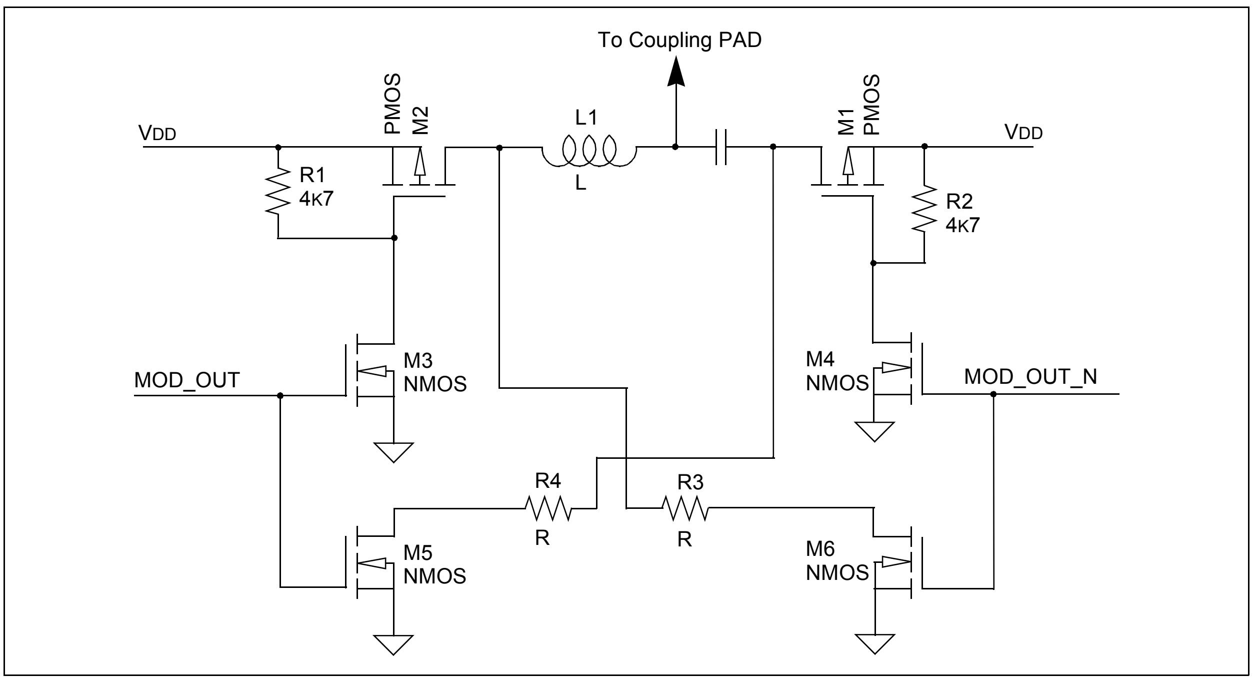
1. **Half-Bridge MOSFET Driver:**
   - uses only one output pin from the PIC microcontroller – modulation output
   - driver tri-state time is high (depends on the R1C1 input constant)
   - touch/proximity detection is difficult without additional circuitry when a common pad is used as coupling element and touch detector
   - touch detection will not work with the CVD technique (high capacitance); other touch detection techniques should be used
   - needs higher voltage than full-bridge configuration for the same performance
   - low component count

FIGURE 8: HALF-BRIDGE MOSFET DRIVER



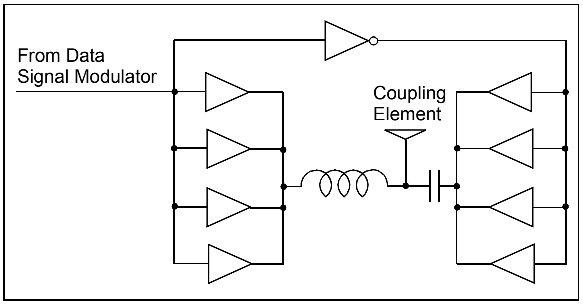
2. **Full-Bridge Bipolar/MOSFET Driver:**
   - the modulation output from the PIC microcontroller needs to be inverted and applied to the driver using the on-chip comparator or an external device (additional resources)
   - has a very low-output resistance in Conducting mode
   - the amplitude of the generated signal is easy to configure using the series output resistor
   - works with wide ranges of power supply voltages (3.3 to 12V)
   - touch/proximity can be done when a common pad is used as the coupling element for touch detection as well (the LC circuitry can be isolated from the ground)
   - higher price/component count than the half-bridge solution
   - best performance/configurability

FIGURE 9: FULL-BRIDGE MOSFET DRIVER



3. **Full-Bridge Driver Using Logic Gates:**
   - needs at least two pins for the driver: modulation output and tri-state output
   - many outputs of the logic gates should be connected together in order to minimize the output resistance of the driver
   - no need for additional circuitry/connection to tri-state its outputs when gates with tri-state capabilities are used
   - works only for voltages below 5V
   - low components count
   - easy to be debugged

FIGURE 10: FULL-BRIDGE DRIVER USING LOGIC GATES



4. **Full-Bridge Driver Using MOSFET Drivers with Output Enable Capabilities (MCP14Ex Family)**
   - needs two pins for the driver: modulation output and tri-state output
   - low-output resistance
   - tri-state capabilities
   - works only for voltages greater than 4.5V
   - lowest components count
   - easy to be debugged.

Table 1 is a comparison of the driver configuration described previously.

FIGURE 11: FULL-BRIDGE DRIVER USING INTEGRATED MOSFET DRIVERS

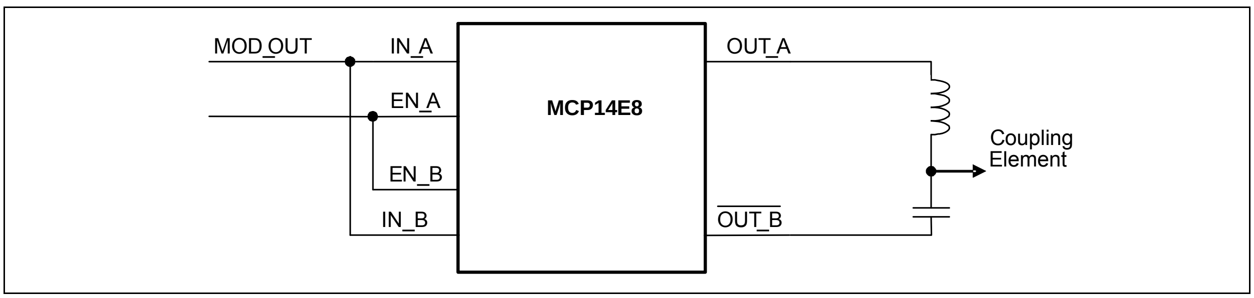


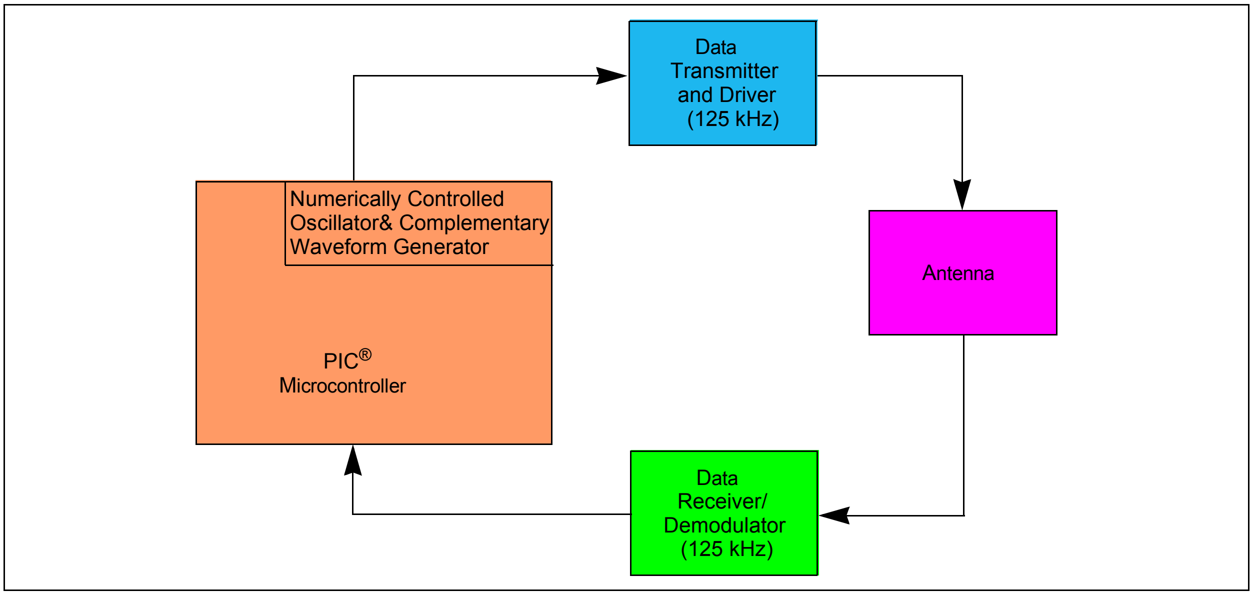
TABLE 1: DRIVER COMPARISON

	Single Ended @9V	Full-Bridge using Logic Gates @ 5V	Full-Bridge MOSFET Transistors @ 5V	Full-Bridge using MOSFET Driver @ 5V	Full-Bridge using MOSFET Driver @ 9V
Driver complexity	Medium	Low	High	Lowest	Lowest
Driver output voltage	+++	+	+++	++	++++
Cost	Low	Low	Medium	High	High

MOBILE UNIT BLOCK DIAGRAM

In a BodyCom system, the mobile unit should be able to receive and process the incoming data, and send back an answer, all performed with very low-power consumption. Figure 12 is a basic diagram of the mobile unit.

FIGURE 12: MOBILE UNIT BLOCK DIAGRAM



On the market, there are integrated devices for data reception/demodulation with very low-power consumption, but the working frequency is limited to 60-400 kHz. The frequency should be generated on the base unit with minimum PIC microcontroller hardware resources. With this in mind, the receiving frequency of the mobile unit is 125 kHz.

For the data reception/demodulator, the AS3933 was chosen; it will allow very low-power consumption while waiting for challenge. It is a highly integrated, low-frequency receiver used in low-power RFID applications. It performs data filtering/amplification/ detection with minimum power consumption, without the need of processing power from the PIC microcontroller.

On the microcontroller side, a PIC MCU with low-power capabilities is recommended (XLP series). In addition, this microcontroller should be able to decode all incoming signals with minimum power consumption. If an answer is necessary, the microcontroller should be able to generate an On-Off Key (OOK) modulated signal (with a frequency range between 60 and 400 kHz).

On the current design, PIC16F1509 was chosen for its multiple resources, which allow users to develop a custom application starting from the current design, without major hardware and firmware changes. PIC16F1509 is a member of the XLP family, with a power consumption bellow 100 nA in Sleep mode. The frequency of the transmitting channel is generated using the Numerically Controlled Oscillator, a peripheral featured in this family of microcontrollers.

Note:	Due to the bidirectional symmetry that BodyCom offers, the exact hardware configuration can be utilized for both the base and mobile units.

MOBILE UNIT – OPERATING MODE

In Normal Operation mode, at power-up, the PIC microcontroller performs all initialization of AS3933 and the internal peripherals, then switches to Sleep mode to lower power consumption. A signal received from the coupled element crosses L1; it has little importance for these frequencies (125 kHz), and is applied to the AS3933 input through a capacitor. The AS3933 is programmed to perform a preliminary filtering of the incoming data stream (and minimizes the false wake-up of the PIC microcontroller).

If the signal meets the 32-bit filter data programmed inside of AS3933, this chip will start to output the data stream. The PIC microcontroller wakes on the first rising edge and starts processing/decoding the received data as it comes in. Once all of the data is received, the PIC microcontroller starts processing/decoding the received data. An answer is sent back using an 125 kHz OOK modulated signal.

The output data string is transmitted using bit-banged Manchester, modulated with the 125 kHz signal, generates using the NCO and CWG. The square-shaped sequence is then applied to a driver working with a series resonant LC circuit.

After the answer sequence is sent, the microcontroller deactivates all internal circuitry and switches back to the Sleep state.

FIGURE 13: MOBILE UNIT STATE DIAGRAM

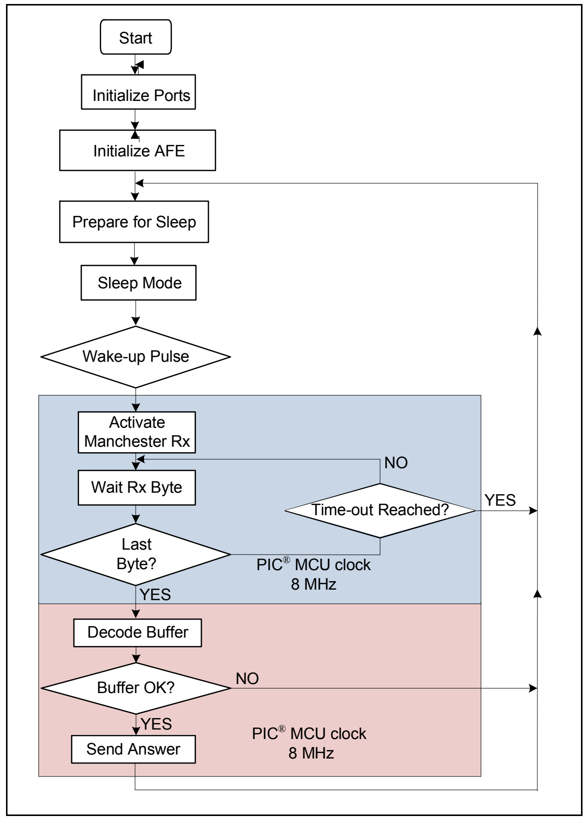


TABLE 2: MOBILE UNIT TYPICAL POWER CONSUMPTION (PRELIMINARY)[1]

	Wait for Signal	Receive Data	Decode Data	Send Answer
AS3933	Wait for signal (2 µA)	Decode data (10 µA)	Wait for signal (2 µA)	
PIC18LF1827	Sleep (<1 µA)	PIC® MCU clock: 8 MHz (1.3 mA)	PIC® MCU clock: 8 MHz (1.3 mA)	
Tx Driver	OFF (0.1 µA)			ON (25 mA)
Time (for 1000 baud rate)	NA	5 ms + (1 ms * Nbytes)	< 1 ms	16 ms + (1 ms * Nbytes)
Power Consumption	3 µA	1.3 mA	1.3 mA	27 mA

Note 1: For 3V supply voltage.

AS3933 AFE DESCRIPTION

AS3933 is a highly integrated configurable device used for low-frequency data demodulation/decoding. The device's high input sensitivity (as low as 80 uV_{RMS}) and ability to detect weakly-modulated input signals, with its low-power feature set, makes the device suitable for various applications.

The AS3933 has an internal configurable, output enable 16 or 32-bit wake-up pattern. The purpose of this pattern is to enable the demodulated data output and wake the external microcontroller only after receiving a specific data sequence on the input pins. Therefore, it prevents waking up the external microcontroller due to noise or unwanted input signals. The circuit compares the first 16 or 32 bits of input data to a pre-programmed value, and enables the demodulated data output when a match occurs.

See the AS3933 data sheet for specific configuration commands.

MOBILE-TO-BASE TRANSMISSION

With the BodyCom system, the coupling element is shared by the receiver and the transmitter.

For transmission, an 125 kHz OOK modulated signal with an amplitude of about 75V peak-to-peak should be generated on the coupling element. A square-wave OOK modulated signal is generated using the on-chip NCO and CWG and is applied to a driver that works with an LC circuit in Resonant mode. The resonant frequency of the LC circuit can be calculated:

EQUATION 11: RESONANT FREQUENCY

$$f = \frac{1}{2\pi\sqrt{LC}}$$

Reactive components such as capacitors and inductors are often described as quality factor Q. While it can be defined in many ways, its most fundamental description is a measure of the ratio of stored vs. lost energy per unit time:

EQUATION 12: QUALITY FACTOR

$$Q = P_{LC} / P_{AVG}$$

Generally, an ideal active element (L or C) stores the energy:

EQUATION 13: ENERGY STORED IN L&C

$$P_{LC} = \frac{1}{2} * \omega_0 * L * I_{pk}^2 = \frac{1}{2} * \omega_0 * C * V_{pk}^2$$

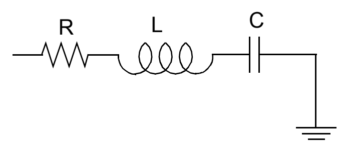
and is lost due to the resistive component of the same components:

EQUATION 14: ENERGY LOST BY RESISTANCE

$$P_{AVG} = ½ * R * I_{pkpk}^2 = ½ * 1/R * V_{pkpk}^2$$

If we consider an example of a series resonant circuit:

FIGURE 14: RLC SERIES CIRCUIT



At resonance, the reactances cancel out, leaving just a peak voltage, V_{pkpk}, across the loss resistance, R. Thus, $I_{pkpk} = V_{pkpk} /R$ is the maximum current which passes through all elements.

In terms of the series equivalent network for a capacitor shown above, its Q is given by:

EQUATION 15: QUALITY FACTOR (CAPACITOR)

$$Q = \frac{1}{\omega_0 * R * C}$$

Since this Q refers only to the capacitor itself, in isolation from the rest of the circuit, it is called unloaded Q or QU. The higher the unloaded Q, the lower the loss. Notice that the Q decreases with frequency.

MOBILE UNIT LC DRIVER REQUIREMENTS

This application note will not describe how to design an LC driver in Resonant mode, but will cover different driver typologies that can be used on the board, with some advantages and disadvantages for each typology used in the past; the user should choose the best version for a specific design.

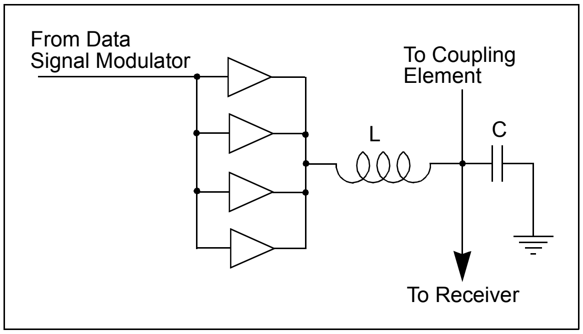
The following are recommended when a new driver is used:

- Should have a low complexity and cost
- Should work at low voltage (minimum 2.2V)
- Should have minimum power consumption in Sleep/waiting for Signal mode
- The output impedance should be very low in Transmission mode and High Z in Receiving mode
- Should be able to drive the LC circuit at 125 kHz in Resonant mode
- The transition from on-to-off state of the modulated signal should be smooth

It is possible to use the exact hardware for both mobile and base units, which is what was done for this reference design. The following are two other examples of topologies that may be used if power consumption is a major factor:

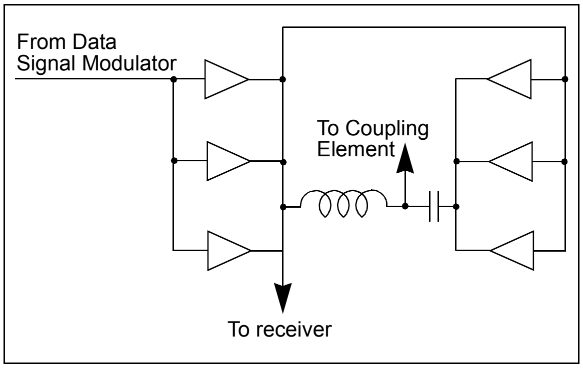
1. **Single ended driver** has the lowest output impedance. The main disadvantage of this configuration is the capacitor connected between the coupling pad and the ground; this capacitor acts like a short during the reception for low frequency and decreases the sensitivity of the mobile unit.

FIGURE 15: MOBILE UNIT – SINGLE ENDED LC DRIVER EXAMPLE



2. **Full-bridge driver** also has a low output impedance. Because of this configuration, the decrease in sensitivity caused by the capacitor situated between the coupling element and the ground is eliminated. By using this configuration, the amplitude of the square wave signal to the LC ends will be double than when a single ended driver is used.

FIGURE 16: MOBILE UNIT – FULL-BRIDGE LC DRIVER EXAMPLE



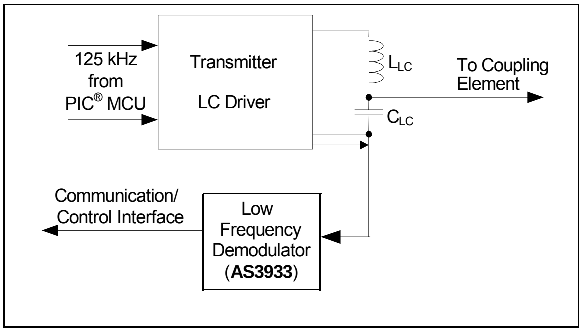
To minimize the power consumption during reception and in Sleep mode, the driver needs to be tri-stated by cutting off its power supply using a power switch. This method can be used because small signals are applied during the reception and those signals will not affect/ damage the unpowered device.

Note:	The power switch used should have very low output impedance for all working voltages (2.2 to 3 Volts). The user should use an active element (MOSFET in this design) that has ensured operation for all voltage range.

BASE UNIT RECEIVER OVERVIEW

The receiving block is a complete receiver solution, including a pre-amplifier, step-down mixer, filters and a data demodulator.

FIGURE 17: RECEIVER SCHEMATIC



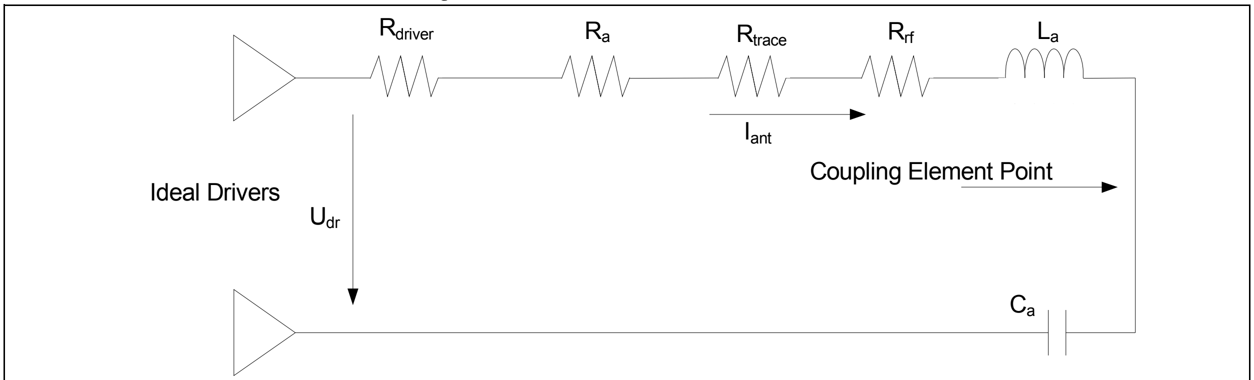
The signal sequence generated by the mobile unit is capacitively coupled with the base unit receiver through a coupling element. The incoming data crosses capacitor CLC and is applied directly to the AS3933.

The resulted signal is applied to AS3933, which performs additional filtering and decodes the incoming data. The data stream is then received by the PIC MCU via a bit-banged Manchester interface. If the received stream is decoded correctly, and the answer is according to the sent challenge, the PIC MCU will perform a specific action (e.g., displays a message on the EUSART).

In order to have a robust communication, a retransmission mechanism is implemented when the received data has errors or no data is received. Additionally, on both units, a EUSART is enabled for interfacing with a PC or an additional microcontroller. This allows another device to control, configure, or test the BodyCom module. Commands for interfacing in this method are discussed in the Firmware section.

The driver and LC circuit driving coupling element can be transformed using ideal components into the following equivalent circuit:

FIGURE 18: TRANSMITTER EQUIVALENT CIRCUIT



where:

R_{driver} = driver resistance and

Ra = current adapting resistor

R_{trace} = resistance of connections leads on PCB

R_{rf} = winding resistance of inductor

Because R_{trace} is very low compared to other elements, it can be ignored.

The maximum current flows when in optimally tuned conditions. It equals:

EQUATION 16: CURRENT THROUGH THE PAD (TUNED)

$$\widehat{I}_{ant_{max}} = \frac{\widehat{U}_{driver}}{R_{LC}} = \frac{4}{\pi} * \frac{V_{DD}}{R_{LC}}$$

The term $4/\pi$ transforms the amplitude of the rectangular driver voltage to the equivalent sine voltage, which is the fundamental of the rectangular signal.

Starting from the previous equation, the maximum allowed resistance can be calculated for a specific current.

Example:

Base Unit: V_{DD} *= 5V and Iantmax = 50 mA →* R_{LC} *= 127.5Ω*

Mobile Unit: V_{DD} *= 2.2V and Iantmax = 25 mA →* R_{LC} *= 112Ω*

Choosing the inductance is not critical. However, the quality factor is determined by the inductance and resistance by:

EQUATION 17: QUALITY FACTOR (INDUCTOR)

$$Q = \frac{\omega_0 * L}{R_{LC}}$$

While Q increases, the data transfer bandwidth reduces creating an upper limit for the LC quality factor. For the BodyCom system, an upper limit of 20 is recommended for quality factor. From the formula given above, the maximum inductance can be calculated from R_{LC} and Q.

Example:

Base Unit: R_{LC} = 127.5Ω and Q = 20 → ≤3.17mH

Mobile Unit: R_{LC} = 112Ω and Q = 20 → ≤11.2µH

The capacitance of the tuned LC circuit can be calculated using this formula:

EQUATION 18: RESONANT FREQUENCY

$$f = \frac{1}{2\pi\sqrt{LC}}$$

Example:

Base Unit: L=1mH, f_0 = 125 kHz → C= 1.62 nF

Mobile Unit: L=4.7µH, f_0 = 8.00 MHz → C= 84.3 pF

Note: The mobile unit parasitic capacitance of the coupling pad (20-30 pF) appears in parallel with physical capacitance of the LC circuit. So, the assembled value for the LC circuit should be the difference between the resulted capacitance (84.3 pF, in this example) and the parasitic capacitance. The parasitic capacitance can be evaluated by measuring the capacitance between the coupling pad and ground, when the mobile unit is not powered.

The maximum voltage on the coupling element point can be calculated with the formula in Equation 19:

EQUATION 19: MAXIMUM VOLTAGE ON THE COUPLING ELEMENT

$$\widehat{U}_{LCpkpk} = 2 * \widehat{U}_{LC_{max}} = 2 * \omega_0 * L * \widehat{I}_{ant_{max}}$$

$$\widehat{U}_{LCpkpk} = 2\omega_0 L \frac{4}{\pi} * \frac{V_{DD}}{R_{LC}}$$

EXAMPLE 1: MAXIMUM VOLTAGE EXAMPLE

Base Unit: L=1mH, f_0 = 125 kHz → $\widehat{U}_{LCpkpk} \cong 80V$

Mobile Unit: L=4.7µH, f_0 = 8.00 MHz → $\widehat{U}_{LCpkpk} \cong 12V$

For a custom design, the current can be adapted to the desired value by changing the current adapting resistor from the output of the driver (*Ra*).

FIRMWARE (API FUNCTIONS)

The BodyCom Evaluation board can be interfaced with a PC or an additional microcontroller using the on-board EUSART. The firmware stack allows an easy implementation of the custom design using the following high level API commands:.

BodyCom Module API – Data Link Layer

It is also possible to create a custom BodyCom application using the following lower level firmware commands.

1. **`BC_BoardHardwareInit()`** – init function that configures hardware peripherals needed by the BodyCom software stack. This function does not provide public arguments or a returned value; the user must make changes via the *"BC_Application.h"* file.
2. **`MDLL_sendPacket(MDLL_PacketData_t* packetData)`** – Transmit function that sends a data packet via the BodyCom interface. The MDLL_PacketData_t type contains the following information:

- Command – Command byte that asks the mobile unit for a specific action.
- Address – This is the 4-byte ID of the mobile unit the base unit is transmitting to. A value of all 1's indicates a general broadcast and all mobile units in range will respond.
- Data Length – The length of the data payload included in the packet. General commands with no data can be sent with a length of zero.
- Data – This is a buffer which contains the data the base is sending.

3. **`MDLL_receiveDataPacket()`** – Receive function that parses the parameters that were sent using the **`MDLL_sendPacket()`** function.
4. **`MDLL_ISR()`** – This function is a state machine that handles transmit and receive functions. The function does not provide public arguments or returned values; the user should use the transmit and receive functions described before A person who uses the BodyCom software stack to develop a custom application should call the **`BC_BoardHardwareInit()`** function before using the transmit and receive functions. After that, the user needs to call **`BC_SendDataCommand()`** to transmit a data packet. The function prepares the data packet and communicates to the state machine (**`MDLL_ISR()`**) to start the transmission.

BodyCom Module API-EUSART

Commands

- `Send Version – "V"`
  - Requests the current firmware version number
- `Send State – "S"`
  - Sets the current operation state

1. `EVAL_TOUCH` – Touch Mode
2. `EVAL_PROX` – Proximity Mode
3. `BC_LEARN_MODE` – Learn Mode
4. `RX_RSSI` – RSSI Mode
5. `RX_PCKT` – Receive Mode
6. `TX_CW` – Transmit Continuous Wave Mode
7. `TX_LPBK` – Transmit Loopback (Echo) Mode
8. `TOUCH` – Display Touch Levels
9. `VIEW_ID` – Display Learned IDs

- `Receive Command – "W"`
  - Builds a custom BodyCom packet
- `Ping ID – "G"`
  - Tells the BodyCom system to send a specific type of ping command

1. `ID_PAIRED` – Pings all currently learned IDs sequentially
2. `ID_ALL` – Pings a general broadcast which pings all IDs in range at the same time
3. `ID_INDEX` – Pings a specific pre-learned ID from its list stored in memory
4. `ID_LEARN` – Pings a general broadcast and adds the first received and unlearned ID to its learned list

- Board Status – "U"
  - Request to send a status update of the current boards state

1. `Pc_App_Rx_TouchPckt – "0"`
   - Sends touch data
2. `Pc_App_Rx_RssiPckt – "1"`
   - Sends RSSI levels
3. `Pc_App_Rx_MobileData – "2"`
   - Sends most recent received packet data
4. `Pc_App_Rx_Pckt – "3"`
   - Sends a custom dummy command for development
5. `Pc_App_Rx_ReadList – "4"`
   - Reads paired ID from memory at a specific index
6. `Pc_App_Rx_ListDelete – "5"`
   - Deletes all paired IDs
7. `Pc_App_Rx_ListAdd – "6"`
   - Adds an ID to the list
8. `Pc_App_Rx_Status – "X"`
   - Sends current BodyCom state and the number of paired IDs
9. `Pc_App_Rx_NewCmd – "N"`
   - Blank. Used for new development

OTHER DESIGN REQUIREMENTS:

To optimize the performance of the system and minimize the signal-to-noise ratio, the following rules are recommended:

- Separate ground planes for the digital and analog sections
- Remember to separate the ground reference and signal coupling pad as much as possible to give the greatest differential coupling between the body and the environment.
- The addition of parallel LC tanks on the other two AS3933 inputs could increase signal reception by picking up more of the radiated energy.

Q&A FOR BODYCOM

Q1: I cannot detect a touch

- Check the touch sensor for shorts
- Check that the ADC input is configured as an input
- Check the threshold level
- Check that the ISR is being called

Q2: I cannot transmit from the Base or Mobile

- Check the oscillator frequency
- Check the configuration of the NCO and CWG peripherals
- Check the wake-up pattern setting
- Check that the APFCON register is set correctly

Q3: I have low output voltage on the Base or Mobile

- Check the signals to the driver
- Check the supply voltage on the driver
- Check for a short on the coupler
- Check that both the normal and inverted signals are at the driver

Q4: I have low output voltage on the Base Unit and the power supply dips during transmit

- Check the polarity of the CWG generating the inverted drive signal

Q5: I have good output voltage on the Base or Mobile, but no modulation

- Check that the NCO and CWG are configured and enabled correctly. Also make sure that the modulation bit is set to N1EN

Q6: I cannot configure the AS393 in the Base or Mobile

- Check that the MSSP is configured correctly
- Check that the APFCON register is set correctly
- Check that the SDI pin is not configured as an analog input in the ANSEL register
- Check that the parity bits are correct in the configuration commands

Q7: My received signal is the right amplitude, but noisy

- Check that there are no loose solder connections

Q8: The signal is getting to the remote, but it does not respond

- Check the checksum calculation
- Check the wake-up pattern settings
- Check that the interrupt-on-change interrupt is configured and enabled

Q9: The remote is responding, but the Base Unit does not see it

- Most likely this is due to the ground reference coupling too closely to the body, which essentially shorts the signal. Try holding the mobile farther away from the torso. Also make sure that you are not touching both the ground pad and the coupling pad equally.
- Check the checksum calculations

Q10: The Mobile stops working if I close my hand around it

- The mobile unit will lose the signal if the user’s hand encloses the unit

Q11: I get a good signal from the Mobile when it starts transmitting, but it fades out

- Check the power supply of the mobile unit; it may not have enough current for transmit. If battery-powered, the battery may be dying.

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2. PIC16F150X Family Data Sheet (http://ww1.microchip.com/downloads/en/DeviceDoc/40001609D.pdf)
3. AN1298 – Capacitive Touch Using Only an ADC (CVD)

APPENDIX A: REFERENCE DESIGN SCHEMATIC

FIGURE A-1: BASE AND MOBILE UNIT DETAILED SCHEMATIC (1 OF 2)

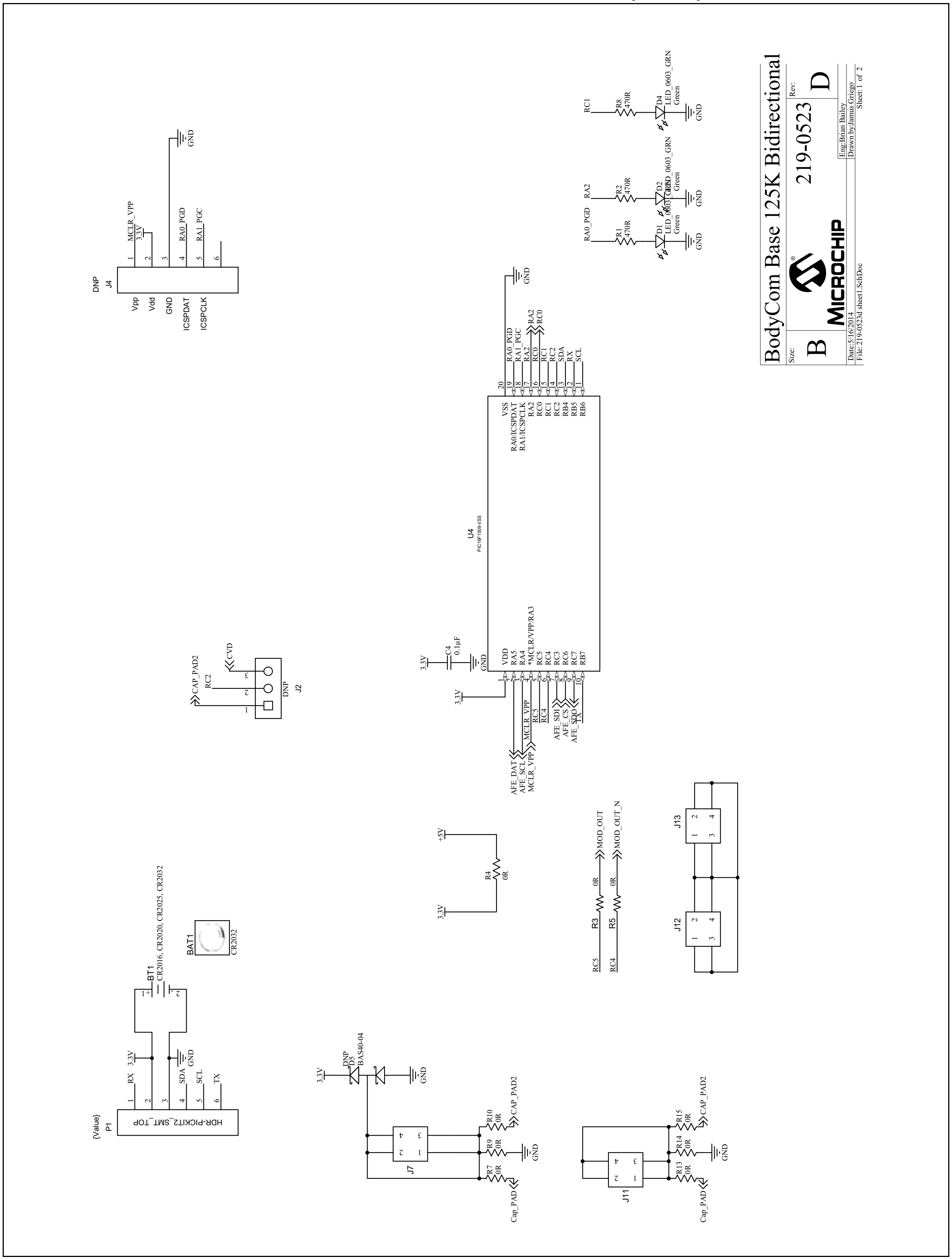
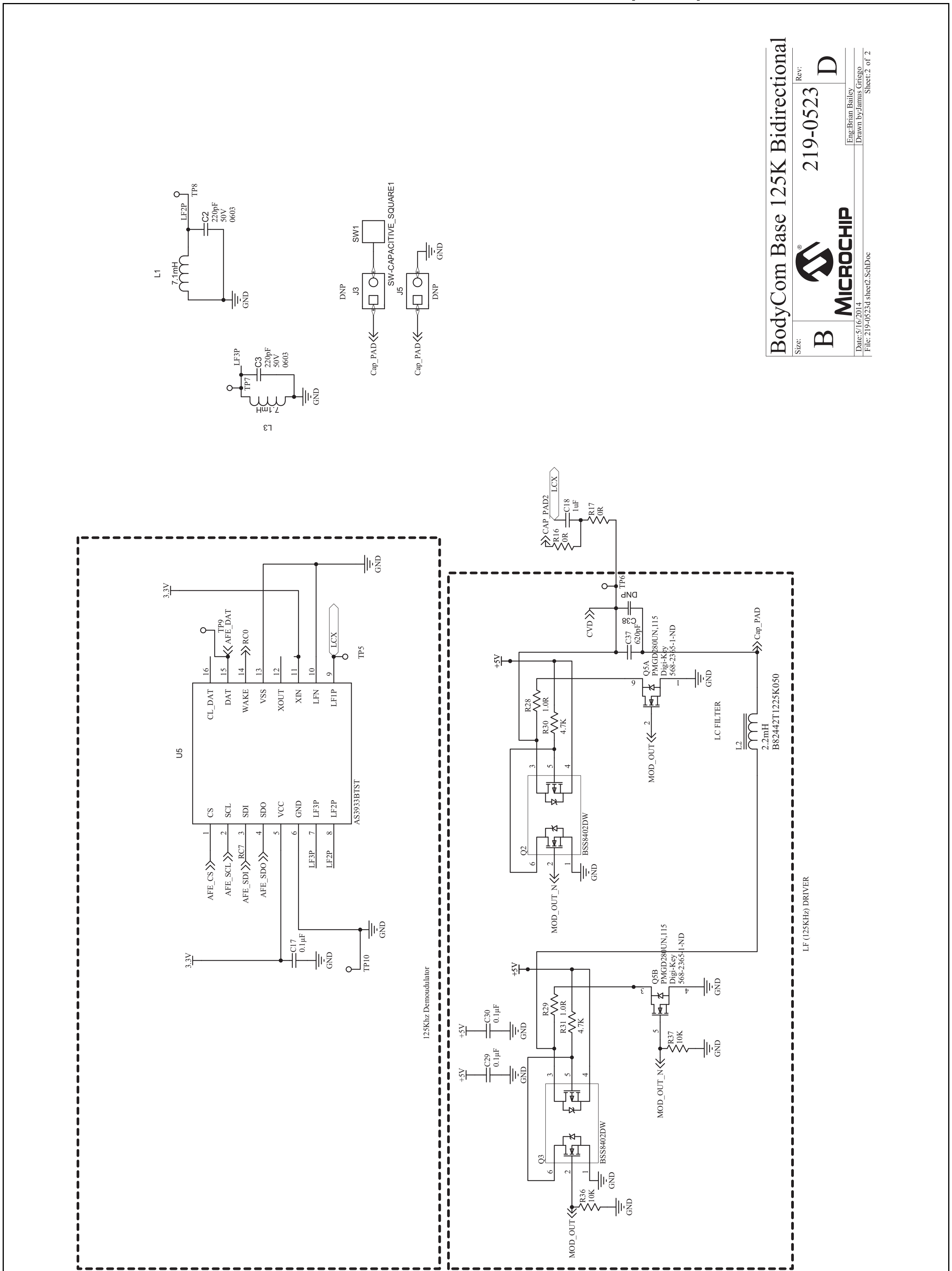


FIGURE A-2: BASE AND MOBILE UNIT DETAILED SCHEMATIC (2 OF 2)



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