

UNIVERSITY OF PUERTO RICO AT MAYAGÜEZ

MAYAGÜEZ, PUERTO RICO

DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING



WaveSphere: Final Report

A REPORT SUBMITTED AS A PARTIAL REQUIREMENT OF THE MICROPROCESSOR
INTERFACING COURSE ICOM-5217

by

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Add Block Diagram for Base Station 2

Add Level Shifters and recalculate power. See if we can find a chart of Charge
vs Voltage to determine the lower level of available charge to get a more real
estimate F-2

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1. Block Diagram

Figure 1 shows a revised system block diagram. It contains the model numbers of the known components, the types of connections required to the microcontroller unit (MCU) and the amount of lines needed for each connection.

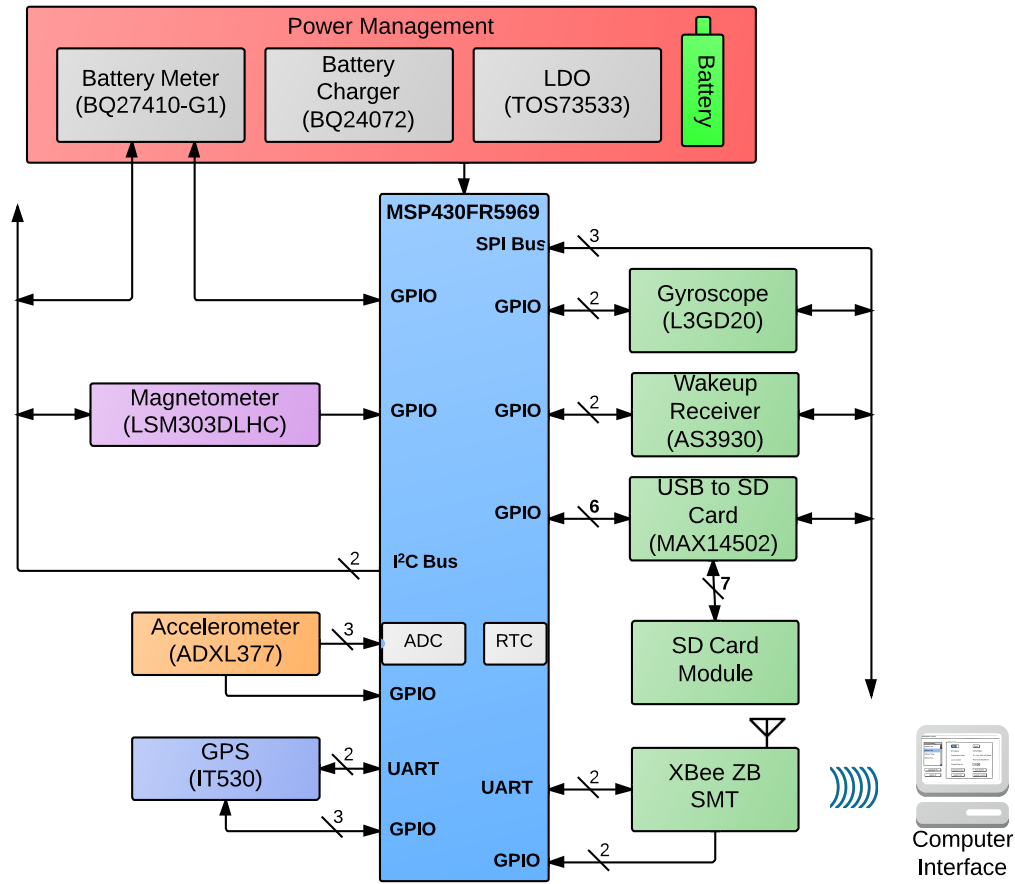


Figure 1: Revised Block Diagram

1. **Microcontroller** - Needed in order to be able to control and establish the communication between components as well as process the output of the sensors.
2. **Battery** - Required to provide the necessary power to the drifters because the electrical components are enclosed by a sphere.
3. **Power Management Circuit** - Composed of an LDO, a battery charger and a battery meter. It is used to regulate the power provided by the battery, re-charge the battery once it has been depleted and to measure the amount of charge left on the battery.
4. **GPS Module** - Needed in order to know the precise location of the drifters when the user has to recover them after they have been thrown at sea for an experiment.
5. **Gyroscope** - Used to determine the rate of change of the orientation of the drifter while being carried by a wave.

6. **Accelerometer** - Used to measure the acceleration of the drifter while being carried by the waves.
7. **Magnetometer** - Used to determine the orientation of the drifter with respect to the Earth's magnetic north while it is being carried by a wave.
8. **Analog to Digital Converter (ADC)** - Needed in order to take the data from the accelerometer, which has an analog output, and convert it to digital signals so that the MCU can read them. It is integrated within the MCU.
9. **SD Card and SD to USB Converter** - The SD Card is used to save the data captured by the sensors during an experiment. The SD to USB converter will be used to allow the drifter to function as a mass storage device when connected to a Host computer via USB.
10. **XBee Module** - Used to connect the spheres with a central base so that data can be retrieved without having to open the spheres.
11. **RF Wakeup Module** - Used to wirelessly wake up the drifter from low power mode via an RF signal.

Add Block Diagram for Base Station

2. Power Analysis

The power analysis consists of four main parts: logic compatibility, driving capability, power supply design and battery life estimate. The purpose of this analysis is to ensure that power requirements for each component are satisfied in order to guarantee their proper functionality. A supporting thermal analysis will be performed on selected ICs.

2.1 Logic Compatibility

Table 1 shows all the digital components in the system along with their input and output digital voltage levels. Only two digital components communicate with each other: the SD Card to USB converter IC and the SD Card itself. It is easy to see from Table 1 that the logic voltage levels between these two devices are compatible. In addition to this, all components communicate with the MCU. It can also be seen that all the devices are logically compatible with the MCU except for the battery gauge, which communicates with the MCU through an I^2C interface and has a V_{DD} of 2.5V. In order to make them compatible, a bi-directional logic level shifter from Texas Instruments was used and can be found in the schematic. It can be seen in the table that by using the aforementioned level shifter, communication between the battery gauge and the MCU is now possible.

Table 1: Component Logic Levels and I/O Currents

Component	V_{DD}	V_{IH}	V_{IL}	V_{OH}	V_{OL}	I_{OUT}	I_{IN}	I_{LEAK}
MSP430FR5969 ¹	3.3	2.1	0.75	3.2	0.2	45 mA ²	50 nA	50 nA
Magnetometer ³	3.3	2.64	0.66	3.3	0	3 mA	10 μ A	10 μ A
XBee	3.3	2.64	0.66	2.706	0.594	4 mA	0.5 μ A	0.5 μ A
RF Wakeup	3.3	1.914	0.99	2.9	0.4	21 mA	100 nA	100 nA
Gyroscope	3.3	2.64	0.66	2.64	0.66	100 μ A	10 μ A	10 μ A
GPS	3.3	2	0.8	2.4	0.4	8 mA	10 μ A	10 μ A
Battery Gauge ⁴	2.5	1.2	0.6	2	0.4	3 mA	10 μ A	0.3 μ A
SD Card ⁵	3.3	2.06	0.83	2.48	0.41	100 μ A	10 μ A	10 μ A
Power Switch	3.3	2.2	1.1	3.3	0	10 mA	0 mA	0.3 μ A
SD Card to USB Converter	3.3	2.06	0.83	2.48	0.41	100 μ A	2 μ A	1 μ A
Level Shifter ⁶	2.5	1.7	0.7	2.5	0	100 μ A	20 μ A	10 μ A

2.2 Driving Capability

In order to ensure that no component draws more current than the one its driver can provide, a weakest driver analysis should be performed. Table 1 shows a list of the available currents found in the data sheets and other sources. The components and their connections are shown in the block diagram depicted in Figure 1.

Since I^2C is a standard, there would be no problems if the level shifter was not present. However, since this component is the weakest driver, the analysis must be performed. The output current of this component is 100 μ A in order to maintain the voltage levels specified in Table 1. It can be seen that this current is greater than the sum of input currents of the components connected to the bus: 10 μ A for the Gyroscope and 50 nA for the MCU.

Since the components connected through UART and Software UART are point to point connections and since the MCU has such a low input and leakage current, the Xbee and GPS modules will not have a problem driving the MCU. Finally, for the SPI Bus, the weakest driver is the Gyroscope with an output current of 100 μ A. It can be seen from Table 1, that this current is greater than the sum of input currents for the other components: 10 μ A for the SD Card to USB Converter and 50nA for the MCU.

With this analysis, one can conclude that all ICs can drive their respective loads

¹ Values used are for the MSP430FR572x as they are not available for the selected microprocessor.

² In full-drive mode

³ Currents obtained from [1]

⁴ Input and output currents obtained from [1]

⁵ Voltages obtained from [2]

⁶ Values for V_{OH} and V_{OL} taken at 100 μ A since the input and output current of the Battery Gauge does not exceed 10 μ A.

2.3 Power Supply Design

In order to design the power supply that will be used by the system, the worst case quiescent current of each component should be taken into account. Although not all components will be operating at the same time, it is ensured that the system will continue to function properly for the worst possible case by performing the analysis in this manner. To ensure proper operation of the system, the Low-Dropout Regulator (LDO) must supply enough current for the entire system. Table 2 shows a list of components along with the worst case quiescent current of each of them. By adding all the current, a maximum current consumption of 181 mA was determined. The LDO is rated for a maximum output of 500 mA, which is well above the determined usage. In order to complete the power supply circuit, a USB Battery Charger and a Battery Meter were added as well. Note that since the level shifters are powered by the 2.5V regulated output of the Battery Meter, they have not been included in these calculations.

Table 2: Worst Case Quiescent Currents for components

Component	$I_{DD(Active)}$ (μA)
MSP430FR5969	1600
3-Axis Accelerometer	300
Magnetometer	110
XBee	45000
RF Wakeup	2.7
Gyroscope	6100
GPS	26140
SD Card	100000
Power switch	1
SD to USB	37
LDO	65
Battery Charger	1500
Battery Meter	103
Total	180958.7

2.4 Thermal Analysis

A thorough thermal analysis was performed on the MCU and all the power management ICs to determine whether they would exceed the thermal limits of their package under regular operation in our system. The expected operating junction temperature was calculated using the junction-to-ambient thermal resistance and the power dissipated by each IC. It was determined that no additional heat dissipation technique as needed to guarantee the proper operation of the ICs since all the calculated junction temperatures were well below the maximum operating junction temperature specified in the manufacturer's datasheets.

The thorough and detailed analysis can be found in Section 2.4.

3. References

- [1] “The I^2C -Bus Specification.” <http://www.nxp.com/documents/other/39340011.pdf>.
- [2] D. Ibrahim, *SD Card Projects Using the PIC Microcontroller*. IT Pro, Elsevier Science, 2010.
- [3] M. Jiménez, R. Palomera, and I. Couvertier, *Introduction to Embedded Systems: Using Microcontrollers and the MSP430*. Springer London, Limited, 2013.

Appendix A: System Specifications

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Appendix B: System Schematics

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Appendix C: Component Layout

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Appendix D: User Guide

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Appendix E: Bill of Materials

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Appendix F: Extended Power Analysis

This section contains a more detailed explanation of how the battery life was estimated. It includes the assumptions made to generate the activity factors. In addition, it includes a thorough description of the calculations made in the thermal analysis.

Add Level Shifters and recalculate power. See if we can find a chart of Charge vs Voltage to determine the lower level of available charge to get a more real estimate

F.1 Battery Life Estimate

In order to estimate the battery life, the average supply current was determined by using a weighted average based on the fraction of time each component is active. The weighted average formula used was: $I_{avg} = \alpha * I_{active} + (1 - \alpha) * I_{LPM}$, where α is the activity factor or the fraction of time the component is active. The following assumptions were made when determining the activity factor.

- The drifters will spend 10 minutes in “Locate Mode” before they are retrieved from the water.
- The drifters will spend 30 seconds in sampling mode.
- The drifters will spend 3 minutes in stand-by mode before they are deployed.
- The drifters will spend about 10 seconds transferring a single data file. The following assumptions were made to determine this time:
 - File Size: 200 kB * 8 = 16,000 kbits.
 - 80% of XBee maximum Speed: 250 kbps * 80% = 200 kbps.
 - 16,000 kbits / 200 kbps = 8 seconds, which can be rounded up to 10 seconds.

Table 3 shows a list of the components along with their active and low power mode supply current, determined activity factor, and weighted average supply current. It also shows the total average current consumption of the system which was determined to be around 70 mA. This means that a chosen 500 mAh battery will last for about 7.23 hours. Based on the current assumptions, a single throw or experiment will last for about 13.66 minutes, which means that the drifters will be able to perform at least 30 experiment trials under the current assumptions.

Table 3: Activity Factors Used to Estimate Battery Life

Component	$I_{DD(Active)} (\mu A)$	$I_{DD(LPM)} (\mu A)$	Activity Factor	$I_{DD(AVG)} (\mu A)$
Connected To LDO				
MSP430FR5969	1600	0.5	78.05%	1248.91
3-Axis Accelerometer	300	0	3.66%	10.98
Magnetometer	110	1	3.66%	4.9894
XBee	45000	0.5	96.34%	43353.02
RF Wakeup	2.7	0.4	0.00%	0.4
Gyroscope	6100	5	3.66%	228.077
GPS	26140	5	73.17%	19127.98

Component	$I_{DD(Active)} (\mu A)$	$I_{DD(LPM)} (\mu A)$	Activity Factor	$I_{DD(AVG)} (\mu A)$
SD Card	100000	10	4.88%	4889.512
Power switch	1	0.3	3.66%	0.32562
SD to USB	37	1	100.00%	37
Connected Directly to Battery				
LDO	65	1	100.00%	65
Battery Charger	1500	6.5	0.00%	6.5
Battery Meter	103	4	100.00%	103
Total	180958.7	35.2	-	69075.69
Battery Capacity	500 mAh	Hours of Use per battery charge		7.238436
Est. time per throw (min)	13.66 mins	Throws per charged battery		31.7785

F.2 Thermal Analysis

Performing a thermal analysis on the system will reveal whether the operating temperature of the individual ICs is below their maximum rating. In order to perform this analysis, the junction temperature T_J will be calculated for the MCU and the power management ICs. The junction temperature is given by [3, 419]:

$$T_J = T_A + \theta_{JA} \cdot P_{diss}$$

where T_J is the estimated junction temperature, T_A is the ambient temperature (taken here to be $27^\circ C$), θ_{JA} is the junction-to-ambient thermal resistance and P_{diss} is the estimated power consumption of the device.

This formula is applied throughout the following sections to determine whether the MCU and the power ICs will be operating at a safe temperature or if they require additional heat dissipation mechanisms such as heat syncs, fans, etc.

F.2.1 Microcontroller

In order to estimate the average operating junction temperature for the MCU the power dissipated by the IC will first be calculated. The following formula, which was taken from [3, 419], will be used:

$$P_{diss} = V_{DD} \cdot \left(I_{DD(avg)} + \sum_{all\ pins} |I_{IO(avg)}| \right)$$

Although no information is available for the θ_{JA} of the MSP430FR5969, since this value depends on the package and the area exposed to the air, a device with the same package (48-pin QFN), the MSP430F5510, was found to have $\theta_{JA} = 28.6^{\circ}\text{C}/\text{W}$ and this value was instead used. In the same manner, although no information on the IO currents is available, the ones for the MSP430F5510 will be used instead.

In full drive mode, the MSP430F5510 can output upto 45mA through its IO pins while still maintaining a valid V_{OL} . Table 4 shows the assumed IO currents for each components.

Table 4: Worst Case IO current for pins

Pin	$I_{DD(Active)}$ (μA)	Qty	Total Current (μA)
SPI	100	3	300
I^2C	10	2	20
UART	1000	2	2000
GPIO	1000	21	21000
Total			23320

Assuming an IO current of 23.32mA and an average supply current of 1.6mA, the total power dissipation can then be calculated to be:

$$P_{diss} = V_{DD} \cdot (1.6m + 23.32m)$$

$$P_{diss} = 82.24mW$$

Using $\theta_{JA} = 47.8^{\circ}\text{C}/\text{W}$, the total junction temperature is then given by:

$$T_J = 27 + 26.8 \cdot 0.08224$$

$$T_J = 29.20^{\circ}\text{C}$$

The datasheet states that the maximum junction temperature is 95°C , which means that in this application, the device is well under the maximum operating temperature rating and no additional heat dissipation mechanism is needed.

F.2.2 Low-Dropout Regulator

The datasheet for the TPS73501 contains a section on power dissipation and provides the following formula for calculating the power dissipation across the device:

$$P_{diss} = (V_{IN} - V_{OUT}) \cdot I_{OUT}$$

The voltage provided by the battery charger circuit is 3.925 V and the required output voltage is 3.3 V. The estimated output current required is 180.96 mA. In order to leave a margin of error, a rounded value of 200 mA will be used in this calculation. Thus, the power dissipated by the device is given by:

$$P_{diss} = (3.925 - 3.3) \cdot 200m$$

$$P_{diss} = 125mW = 0.125W$$

Since for this device, $\theta_{JA} = 47.8^{\circ}C/W$, the total junction temperature is then given by:

$$T_J = 27 + 47.8 \cdot 0.125$$

$$T_J = 32.98^{\circ}C$$

The datasheet states that the maximum junction temperature is $150^{\circ}C$, which means that in this application, the device is well under the maximum operating temperature rating and no additional heat dissipation mechanism is needed.

F.2.3 Battery Charger

The datasheet for the BQ24072 provides the following formula for estimating the power dissipation across the device.

$$P_{diss} = (V_{IN} - V_{OUT}) \cdot I_{OUT} + (V_{OUT} - V_{BAT}) \cdot I_{BAT}$$

The output voltage of the device is 5.5 V, while the input voltage is 5 V as dictated by the USB standard. The output current can be estimated to be 50mA by taking into account the two LEDs connected to this pin (at about 20mA per LED) and the LDO input (46 μA) and rounding up to leave a margin for safety. The circuit was designed for a battery voltage of 3.7 V and a current of 800 mA.

$$P_{diss} = (5 - 3.925) \cdot 50m + (3.925 - 3.7) \cdot 500m$$

$$P_{diss} = 166mW$$

Since for this device, $\theta_{JA} = 39.47^{\circ}C/W$, the total junction temperature is then given by:

$$T_J = 27 + 39.47 \cdot 0.166$$

$$T_J = 33.55^{\circ}\text{C}$$

The datasheet states that the maximum junction temperature is 125°C , which means that in this application, the device is well under the maximum operating temperature rating and no additional heat dissipation mechanism is needed.

F.2.4 Battery Meter

Although the datasheet for the BQ27410 does not provide a direct formula for power dissipation and because the battery meter has an internal LDO, the formula used for the MCU IO pins will be combined with the power dissipation formula of the LDO to obtain a more robust estimate for the power dissipated.

$$P_{diss} = V_{DD} \cdot \left(\sum_{all\ pins} |I_{IO(avg)}| \right) + (V_{IN} - V_{OUT}) \cdot I_{OUT}$$

The IO pin output current for this device is between 0.5 and 1 mA. 1 mA will be used for the two I^2C pins, which gives a total IO current of 2 mA. The maximum supply current is $103\ \mu\text{A}$ and this will be used instead of the average supply current to leave a margin of safety. The input voltage is 5.5 V and the regulated output voltage is 2.5 V.

$$P_{diss} = 2.5 \cdot (2m) + (3.7 - 2.5) \cdot 0.103m$$

$$P_{diss} = 5.12mW$$

Since for this device, $\theta_{JA} = 64.17^{\circ}\text{C}/\text{W}$, the total junction temperature is then given by:

$$T_J = 27 + 64.1 \cdot 0.00512$$

$$T_J = 27.33^{\circ}\text{C}$$

The datasheet states that the maximum junction temperature is 100°C , which means that in this application, the device is well under the maximum operating temperature rating and no additional heat dissipation mechanism is needed.

Appendix G: Work Distribution

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