Sub-microamp Microcontroller and Wireless Transceivers, Protocols, Network Architectures

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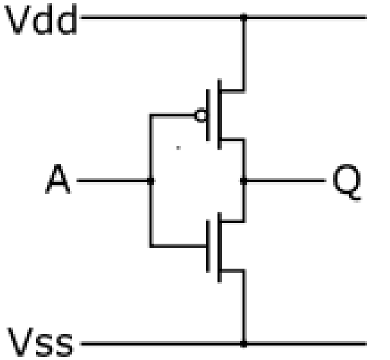
- Mark is responsible for product and marketing strategy as a staff member at Texas Instruments with 25 years experience.
- He has recently driven the introduction of magnetic hall-effect sensors, monolithic automotive MCU-based integrated BLDC motor drivers and creation of the Smart Grid Business Unit.
- He was directly responsibly for the world-wide launch and new product definition of the MSP430 family of ultra-low power microcontrollers.
- Mark has a Bachelors of Science degree in Electrical Engineering from Oakland University in Rochester Michigan.

Agenda

- Standby as the normal mode
- Managing overall system power budget
- Supply voltage
- Power gating sensor
- Sensor measurement
- Importance of energy aware firmware
- EH /WSN Demonstration

ULP Embedded Systems Basics

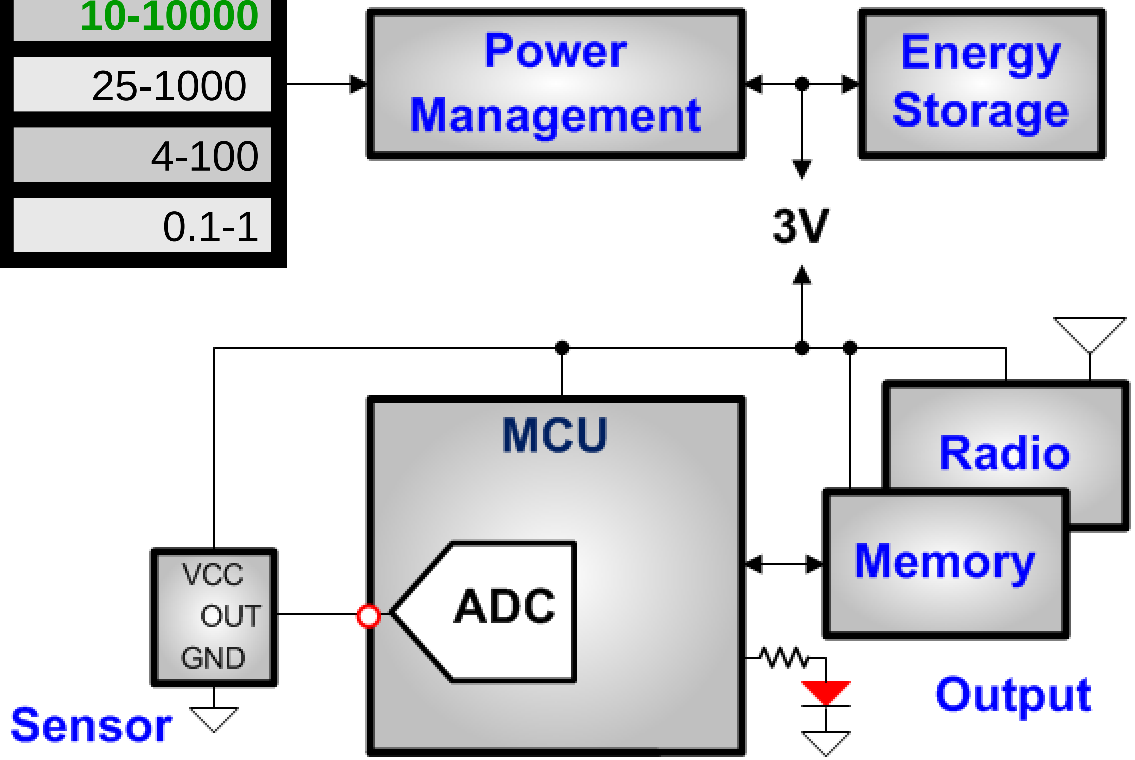
$$P = P_{dyn} + P_{stat}$$
$$= CV^2f + VI_{leak}$$



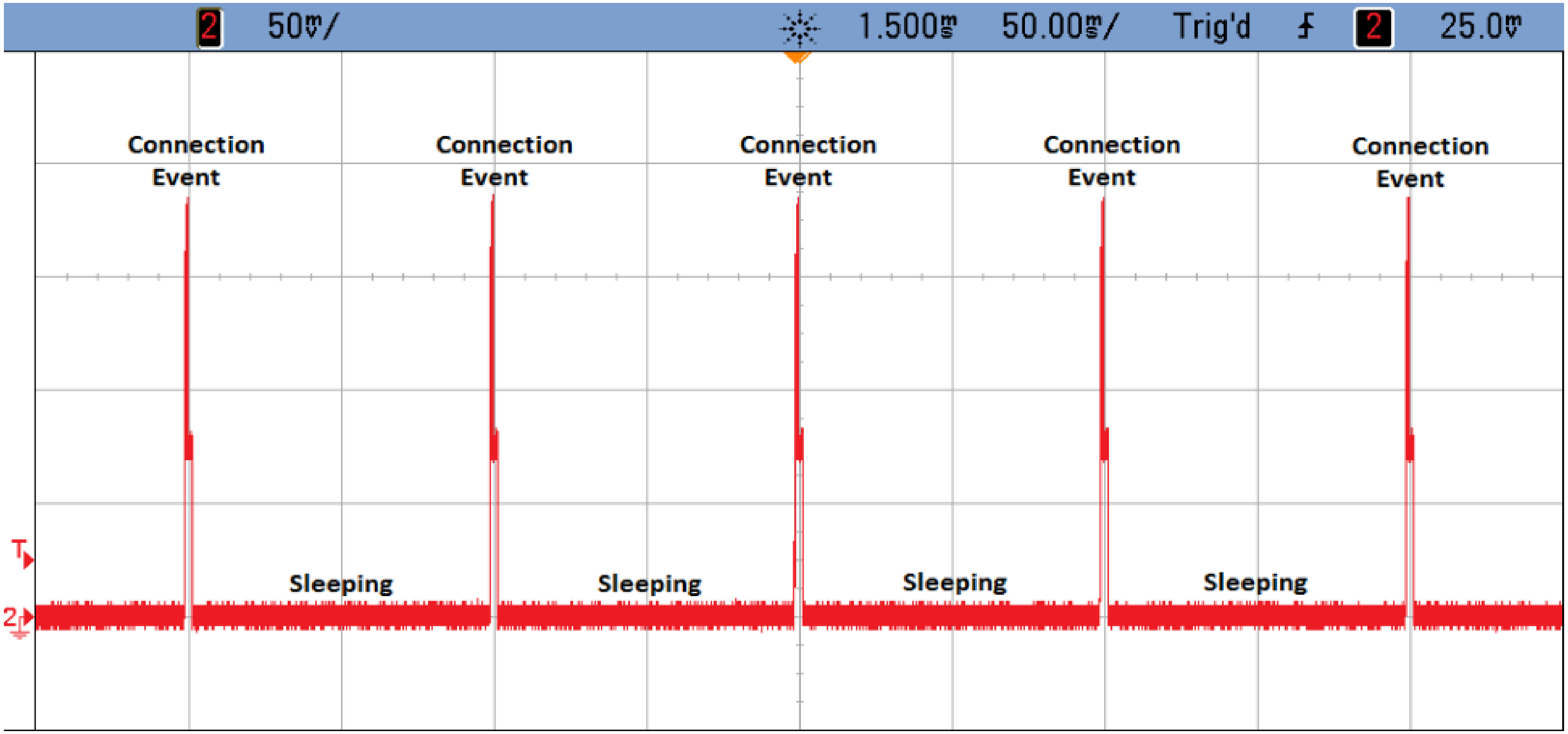
- Both frequency and voltage can be controlled
- Lowering frequency has a linear effect
- Lowering voltage has a squared the effect

Typical EH System ~10 to 100uW

Source	uW/cm2
Solar	10-10000
Thermal	25-1000
Vibration	4-100
RF	0.1-1

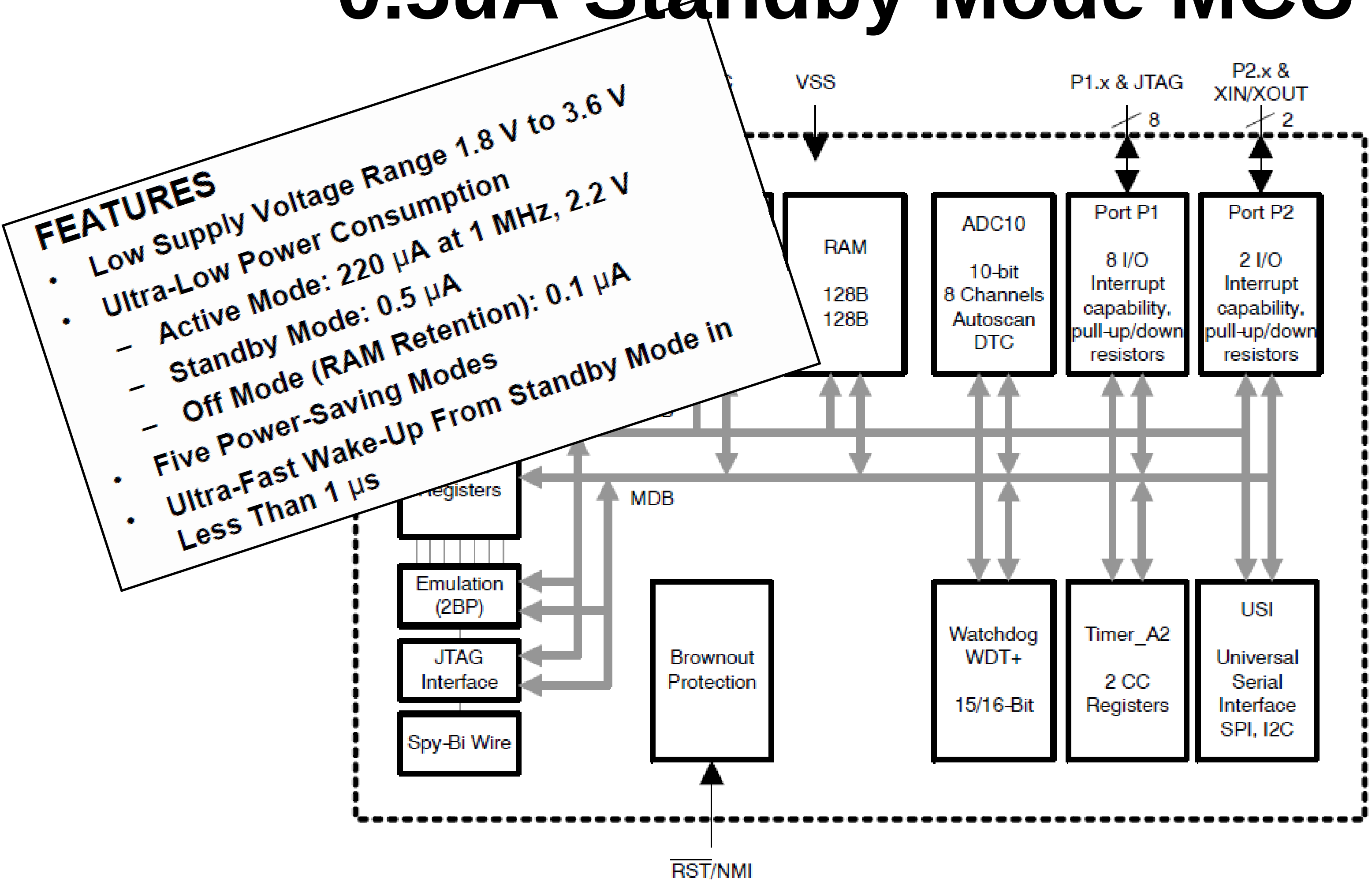


ULP/EH/WSN Typical Activity Profile



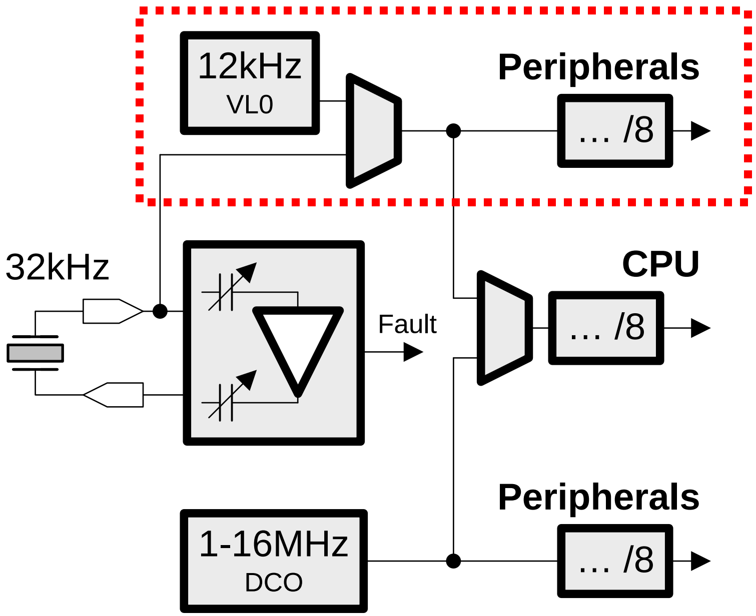
- **Sleep mode as normal mode**
- **Average power approaches sleep**
- **Peaks must not be “extreme”**

0.5uA Standby Mode MCU



- **MSP430F20xx Tiny workhouse since 2005**
- **0.35um single-supply domain, <u>nothing special</u>**

MCU Clocking and Voltage Impact



MSP430F20x from datasheet

	TEMP	VCC	TYP	UNIT
Active 1MHz Flash	N//A	2.2V	**220**	uA
	N/A	3V	**300**	
Standby 12kHz VLO	25° C	2.2V	**0.5**	uA
	85° C		1.0	
	25° C	3V	0.6	
	85° C		1.3	

VLO/8	*22° C*	*2.0V*	*0.3uA*	*uA*

from bench test

- **Active 25% reduction 3V to 2.2V**
- **Standby is the normal mode**
- **Current is for entire chip … clock, memory, BOR …**

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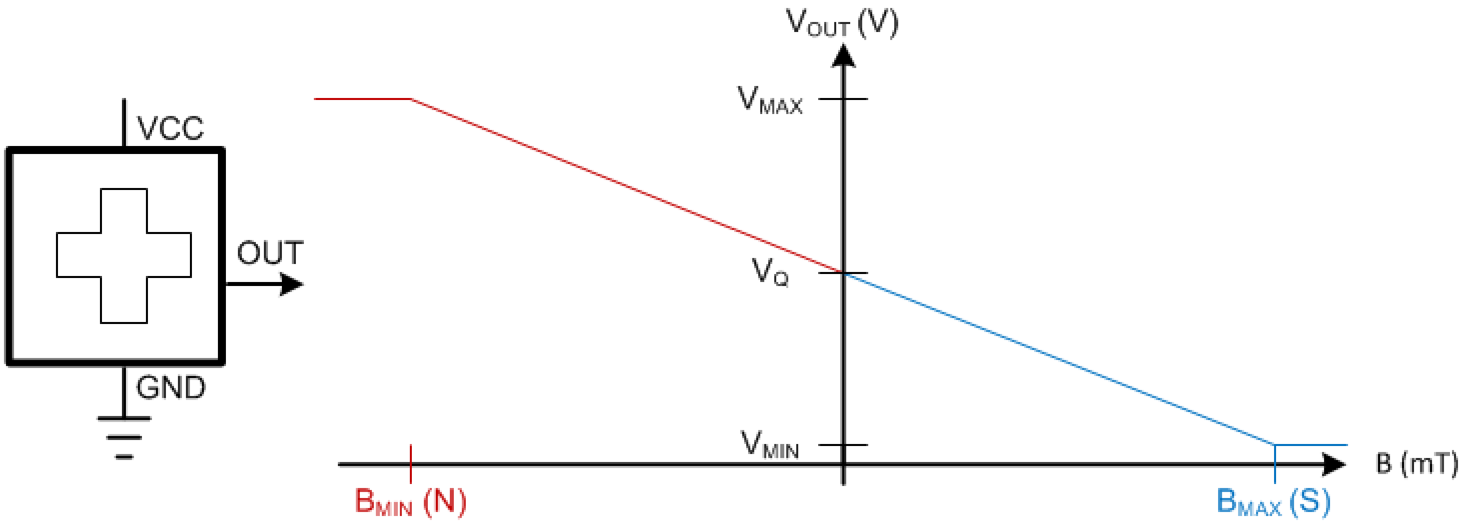
Linear Hall Sensor – VCC, GND and OUT



PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
POWER SUPPLIES (VCC)						
V_{cc}	VCC operating voltage		2.7		36	V
I_{VCC}	VCC operating supply current	V_{CC} = 2.7 ~ 38 V		2	4	mA
t_{ON}	Power-on time				50	µs

Sensor

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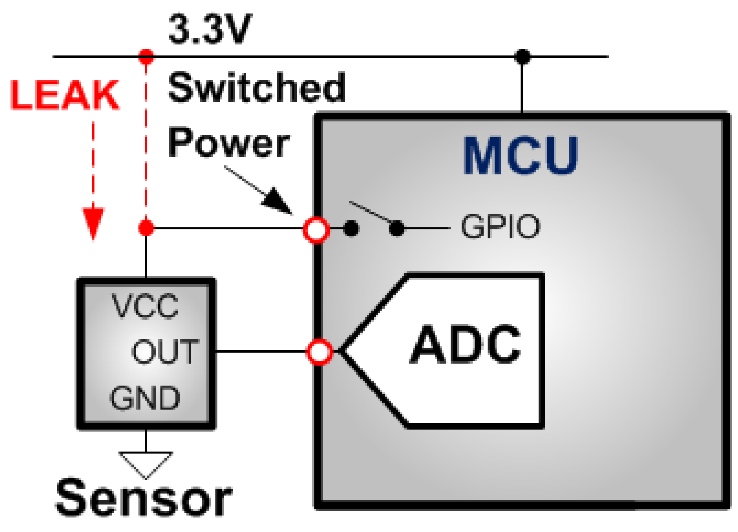
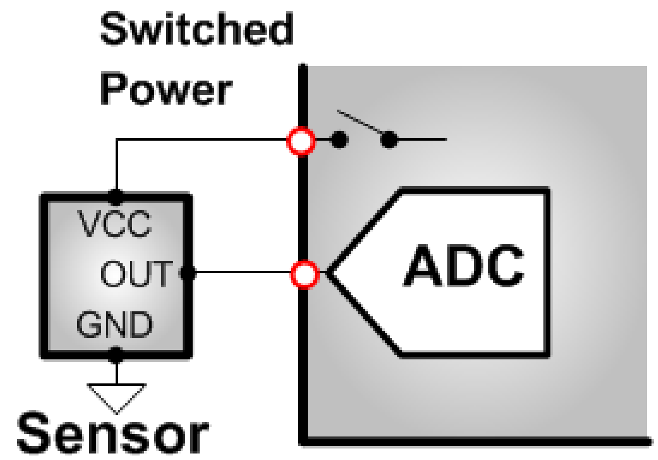
Power Gate External Sensors

- **Power gate sensor to eliminate static Leak**
- **`MeasureSensor();`**
  - 50us
  - @3mA
- **@1Hz Sample**
  - 0.000050*3mA
  - 0.150uA adder on average
- **@3Hz Sample**
  - **0.450uA adder**



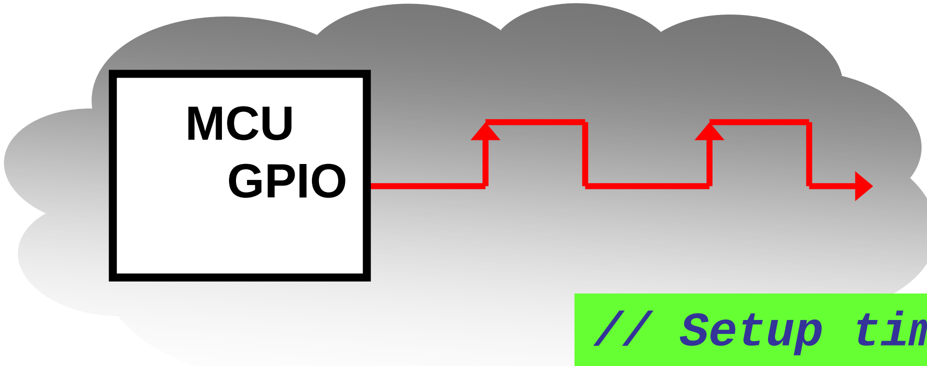
ADC Sensor Sampling

- **ADC10 = 600uA @200kSPS**
  Reference = 250uA
- **@1Hz Sample**
  - 0.004uA = 850uA/200,000
- **@3Hz Sample**
  - **0.012uA adder**



PARAMETER		VCC	MIN	TYP	MAX	UNIT
I_{ADC10}	ADC10 supply current (see Note 3)	2.2 V		0.52	1.05	mA
		3 V		0.6	1.2	mA
I_{REF+}	Reference supply current, reference buffer disabled[(4)]			0.25		mA
				0.25		mA

Energy Aware Firmware



0% CPU Load!

```
// Setup timer output unit
 CCTL1 = OUTMOD0_1;
 _BIS_SR(CPUOFF);
```

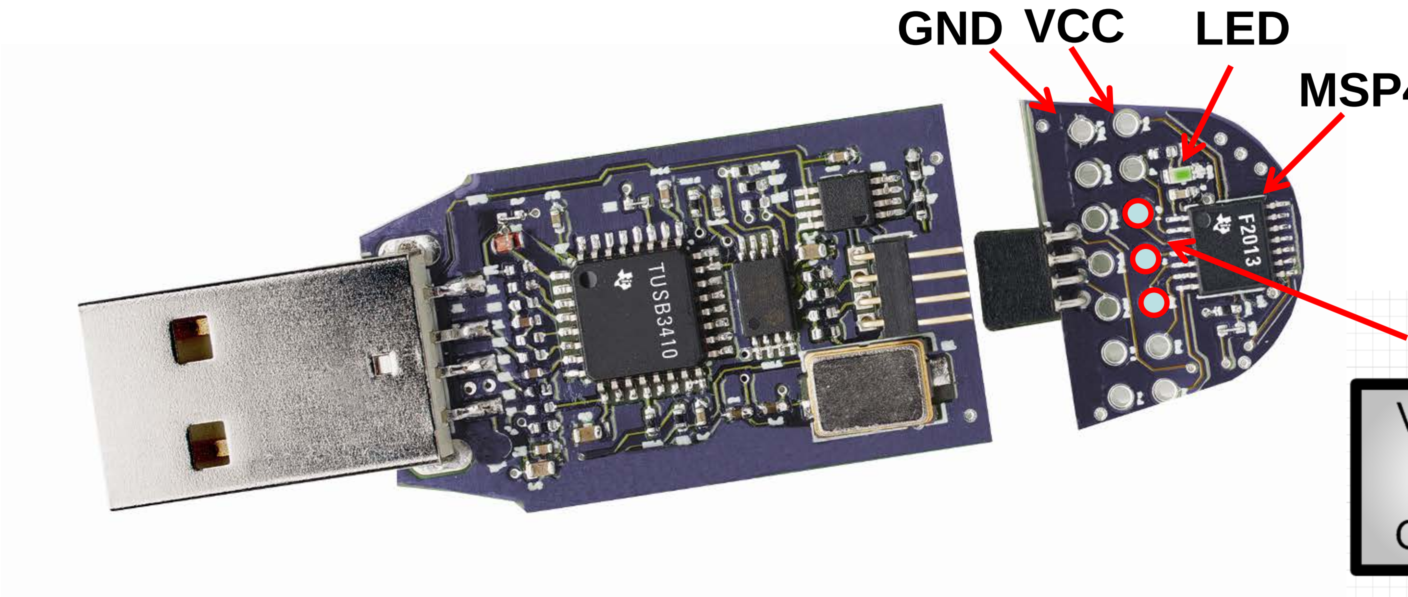
0.01% Load

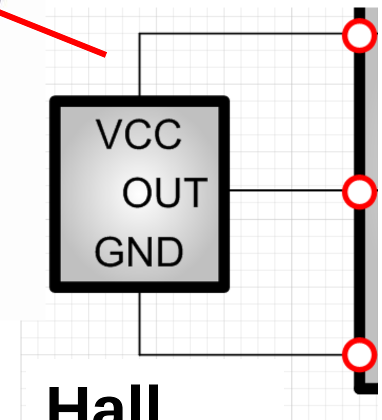
```
#pragma vector=WDT_VECTOR
_interrupt watchdog_timer (void){
  P1OUT ^= 0x01;  // Toggle
}
```

100% CPU Load

```
while (1){
 P1OUT ^= 0x01;           // Toggle
 __delay_cycles(10000);   // Delay
}
```

For Demonstration





Hall Sensor

- **$20 eZ430-F2013 Development tool**
- **LED already on target used as indicator**
- **Magnet Hall Sensor 3-pin added**
- **MCU GPIO used to create Sensor VCC and GND for**
- **MSP430F2013 replaced with MSP430F2012**

>1mA NOT ULP Sensor Sampling Code

```
 P1OUT = HALLPWR;                          // PWR to HALL

while (1)  {
  ADC10CTL0 |= ADC10SC;                    // Sampling start
  while (ADC10CTL1 & ADC10BUSY);           // ADC10BUSY?
  if ((ADC10MEM < 0x182) || (ADC10MEM > 0x1C2))
    P1OUT |= LED;                          // LED on
  else
    P1OUT &= ~LED;                         // LED off
  ADC10MEM_prev = ADC10MEM;
}
```

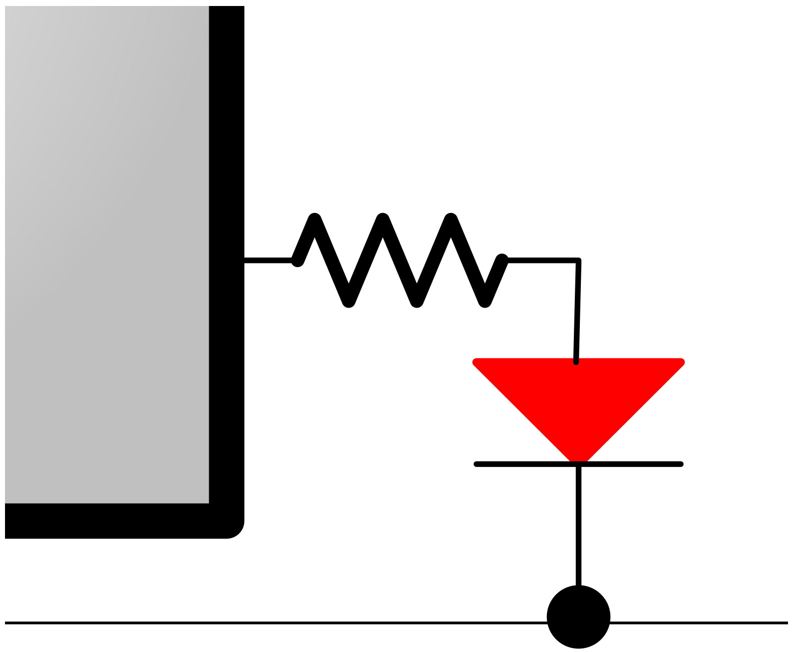
- **Sensor permanently powered**
- **CPU operates full speed in an endless loop**
- **ADC and Reference operate full speed permanently**

1uA ULP Sensor Sampling Code

```
while (1){
  _BIS_SR(LPM3_bits + GIE);      // *NORMAL MODE*
  P1OUT |= HALLPWR;              // *PWR Sensor
  ADC10CTL0 = SREF_1 + ADC10SHT_2 + REF2_5V + REFON + ADC10ON;
  __delay_cycles(50);            // *50us REF and HALL POR*
  ADC10CTL0 |= ADC10SC;          // Sampling start
  while (ADC10CTL1 & ADC10BUSY); // ADC10BUSY?
  P1OUT &= ~HALLPWR;             // *noPWR to Sensor*
  if ((ADC10MEM < 0x182) || (ADC10MEM > 0x1C2)) // 0.9V><1.1V
    P1OUT |= LED;               // LED on
  else
    P1OUT &= ~LED;              // LED off
}
__interrupt void watchdog_timer (void){
  _BIC_SR_IRQ(LPM3_bits);       // Exit LPM3
}
```

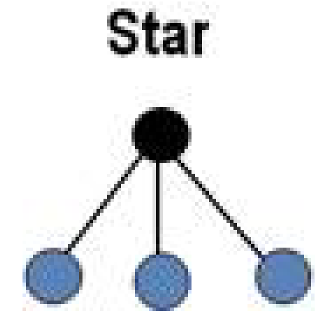
Starting Point … Flashing the LED

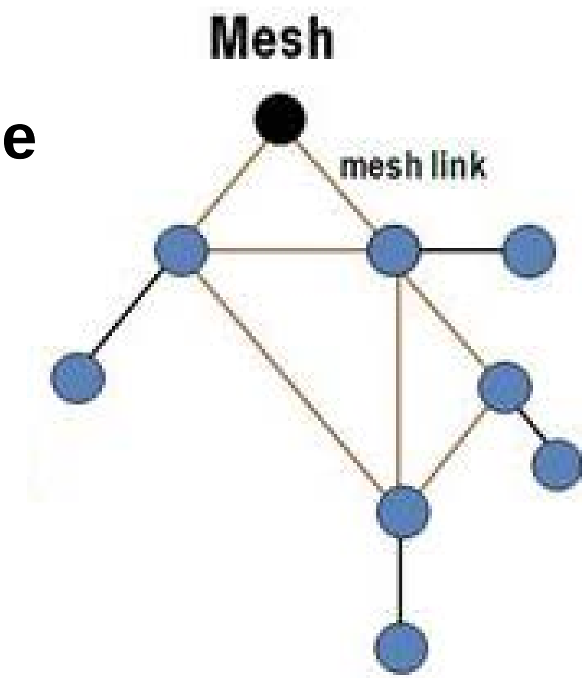
- **Often a marketing must-have for electronic system-functioning-properly indicator**
- **~5mA pulse for 1ms**
- **1/second**
  - 0.1% duty cycle
  - 5uA adder on average
- **1/5 second**
  - 0.02% **duty cycle**
  - **1uA adder**



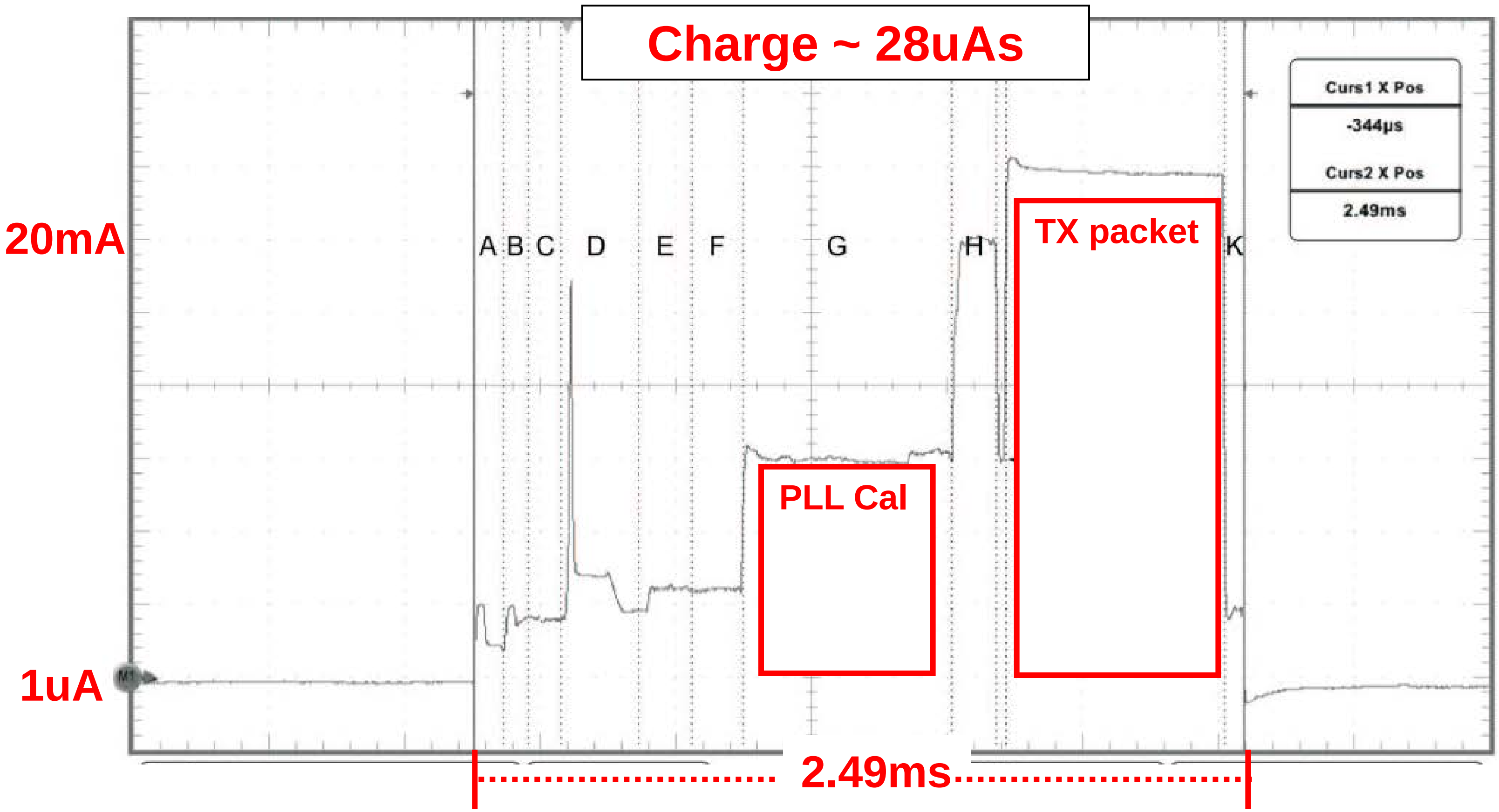
WSN Consideration for EH

- **Ultra-low power consumption**
  - Peak
  - Average
  - Idle
  - Start-up
- **High packet efficiency**
- **Robust and immune to interference**
- **Security**
- **Multi-vendor interoperability**



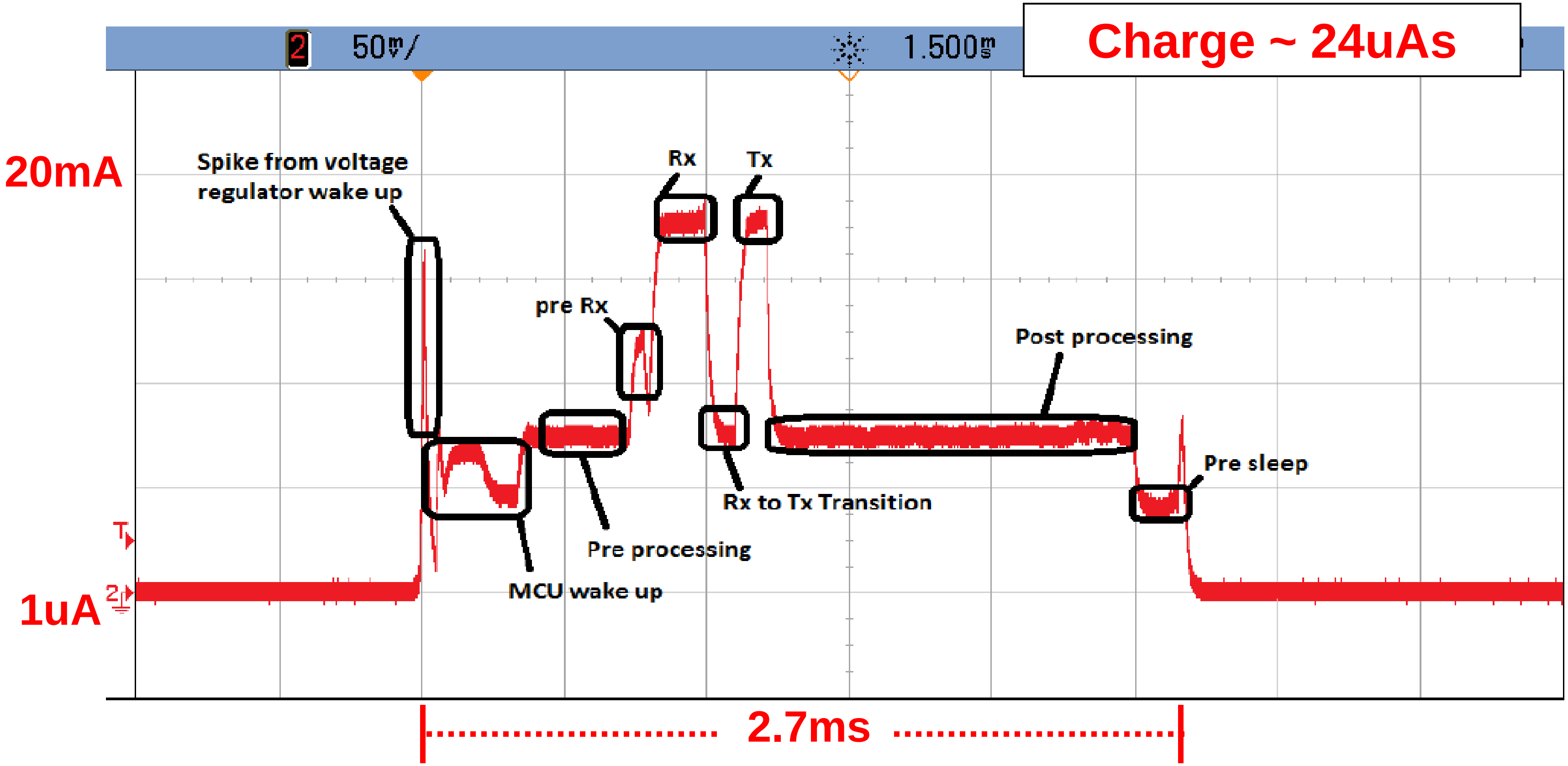


Add WSN Simplicity/e430-RF2500



- **28uA @ 1Hz TX packet interval on average**
- **5.6uA @ 0.2Hz**

Add BLE WSN CC2541



- 24uA @ 1Hz TX packet interval on average
- 5uA @ 0.2Hz

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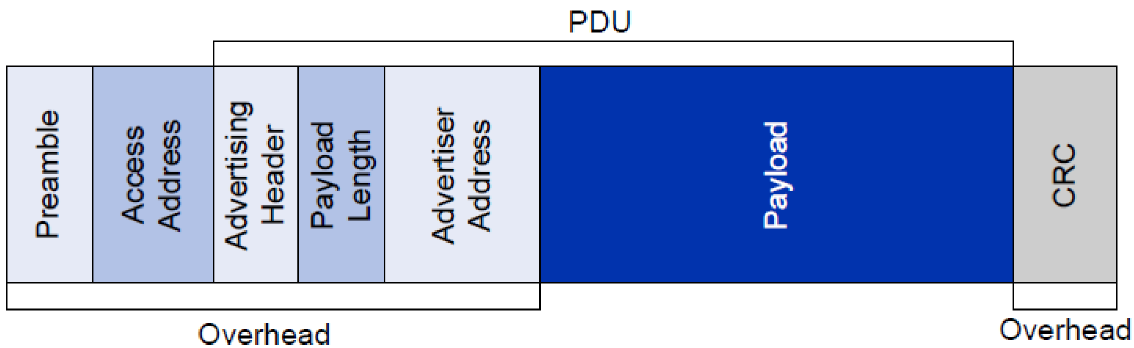
WSN Packet Efficiency




```
Preamble = 1 octet
Access Address = 4 octets
PDU (Protocol Data Unit (packet or message)) = 39 octets
       Advertising Header = 1 octet
       Payload length = 1 octet
       Advertiser Address = 6 octets
       Payload = 31 octets
CRC (Cyclic Redundancy Check) = 3 octets
```

BLE Payload/Total length = 31/47 = 0.66 > 66% efficient

Extra: WSN Choices

Dongle,computer and special GUI

- BLE is standard on Smart Phones and very low power
- ISM special hand-crafted RF and BLE offer comparable power
  … but consider cost of special R&D and support … worth it?
- Any WSN should be low power, robust and noise immune

1uA Sensor Sampling Solution

```
//   MSP430F2012 + DRV5050
//   ----------------------
//   Standby LPM3 = 0.500uA
//   Sensor@3Hz   = 0.450uA
//   ADC10 @3Hz   = 0.012uA
//   Main()       = 0.100uA
//   ----------------------
//   Total @3Hz   ~ 1.100uA     @1Hz  ~0.800uA

//   WSN @0.2Hz   ~ 5.000uA
//   With   LED     6.100uA
```

- **MCU, ADC and Sensors can be managed**
- **WSN is the bottleneck**

Thank You