Energy Consumption Analysis for Bluetooth, WiFi and Cellular Networks

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This document analyzes average energy consumption of Bluetooth, WiFi (802.11) and cellular networks for transmitting data produced at *f* bytes per second. It is assumed that a packet is created every t_{buf} seconds and sent to the respective module for transmission. Thus, data produced by an application in t_{buf} is given by $d = t_{buf} * f$ bytes, neglecting packet overhead.

The different energy and current values used in this report are either taken from data sheets, published papers, or provided by the vendor (in case of Bluetooth).

1. Bluetooth

We consider a BlueCore2 Bluetooth module from CSR. The goal is to analyze power consumption of the module in its low power sniff modes with 40ms, 470ms and 1.28s sniff intervals (T_{sniff}). It is assumed to be in slave mode, with an ACL connection to a master. These settings are typically used in a standard Bluetooth Serial Port Profile. The current consumption values for 40ms and 1.28s intervals are taken from the data sheet, while the values for 470ms interval were provided by AliveTec Inc., which use this module in their wireless heart monitors consisting of an ECG sensor and a 3-axis accelerometer. Thus, it is important to note that this analysis can be easily applied to BlueCore3 module as well, but only for the 40ms and 1.28s intervals with appropriate values from its data sheet. The T_{sniff} interval also determines the latency for data reception at the master.

The configuration of the device containing the Bluetooth module is assumed as follows: An MSP430 microcontroller sampling the sensors using its internal ADC, and sending a packet to the connected Bluetooth module every t_{buf} seconds. The parameter t_{buf} is chosen so as to allow the microcontroller to sleep while enough data is collected to form a single Bluetooth DH1, DH3 or DH5 packet. This configuration is similar to the heart monitor from AliveTec. The MSP430 can set up its DMA to do the sampling, while its core sleeps till the data buffer is ready in its RAM. The device operates at V = 3.7 volts.

1.1 General Power Consumption Model

The Bluetooth slave module operates as follows in its sniff mode with ACL connection to a master: It is in sleep mode by default. It wakes up every T_{sniff} time to listen to the master and transmit all data from its buffer. It consumes $I_{ACL,active}$ during this transmission, and $I_{ACL,connection}$ while asleep and connected to the master.

Total data collected by the Bluetooth module in T_{sniff} interval: $D_{sniff} = d * (T_{sniff}/ t_{buf})$ bytes

Time to transmit D_{sniff} at *b* kbps: $t_b = 8*D_{sniff}/(b*1024) = (8f * T_{sniff})/(b * 1024)$ seconds

Power = V * ($I_{ACL,active}$ * t_b + $I_{ACL,connection}$ * (T_{sniff} – t_b))/T_{sniff} Watts

⇨ Power = V * ($I_{ACL,active}$ - $I_{ACL,connection}$) * t_b + $I_{ACL,connection}$ * T_{sniff})/T_{sniff} Watts

1.2 Specific Models

For an ACL connection in Bluetooth, 3 different packet formats are possible – DH1, DH3 and DH5 – each having a different packet length, thus providing varying bandwidth to the application. Table 1 gives packet lengths and maximum possible bandwidths corresponding to each packet type. For power calculations, we use these values to get the lowest possible power consumption for that configuration.

Packet Type	**Packet Size** (data bytes)	**Bandwidth** (kbps)
DH1 (1 slot)	28	172.8
DH3 (3 slots)	183	585
DH5 (5 slots)	341	733.9

Table 1: Bluetooth packet types for an ACL connection

We consider each sniff interval for our analysis, and further divide it according to the packet type (or bandwidth) desired by the application. Table 2 lists current consumption values for each T_{sniff} interval.

Sniff Interval (T_{sniff}) (ms)	**$I_{ACL,connection}$** (mA)	**$I_{ACL,active}$** (mA)
40	4.0	50.0
470	2.5	50.0
1280	0.5	50.0

Table 2: Current consumption values for different sniff intervals

From tables 1 and 2, and the power consumption model described above, we get the following models for each sniff interval.

Sniff Interval (T_{sniff})	**Packet Type**	**Power Consumption in terms of *f*** (mW)
40ms	DH1	0.0077 * f + 14.8
	DH3	0.0022 * f + 14.8
	DH5	0.0018 * f + 14.8
470ms	DH1	0.0080 * f + 9.25
	DH3	0.0023 * f + 9.25
	DH5	0.0019 * f + 9.25
1.28s	DH1	0.0083 * f + 1.85
	DH3	0.0024 * f + 1.85
	DH5	0.0020 * f + 1.85

Table 3: Power consumption models for Bluetooth low power sniff modes

1.3 Observation

Next, we analyze the above models at different data production rates – 75, 100, 150, 300, 600 and 1200 Hz. We observe that for a fixed data production rate, increasing the sniff interval causes a proportionate decrease in power consumption. But, for a fixed sniff interval, decreasing data production rate does not cause a considerable decrease in power consumption. The comparison is shown in table 4 and figure 1.

Sniff Interval (T_{sniff})	Packet Type	Data Production Rate (bytes/second)					
		75	100	150	300	600	1200
		Power Consumption (mW)					
40ms	DH1	15.3775	15.57	15.955	17.11	19.42	24.04
	DH3	14.965	15.02	15.13	15.46	16.12	17.44
	DH5	14.935	14.98	15.07	15.34	15.88	16.96
470ms	DH1	9.85	10.05	10.45	11.65	14.05	18.85
	DH3	9.4225	9.48	9.595	9.94	10.63	12.01
	DH5	9.3925	9.44	9.535	9.82	10.39	11.53
1.28s	DH1	2.4725	2.68	3.095	4.34	6.83	11.81
	DH3	2.03	2.09	2.21	2.57	3.29	4.73
	DH5	2	2.05	2.15	2.45	3.05	4.25

Table 4: Power consumption values for specific data production rates for all sniff modes and packet types

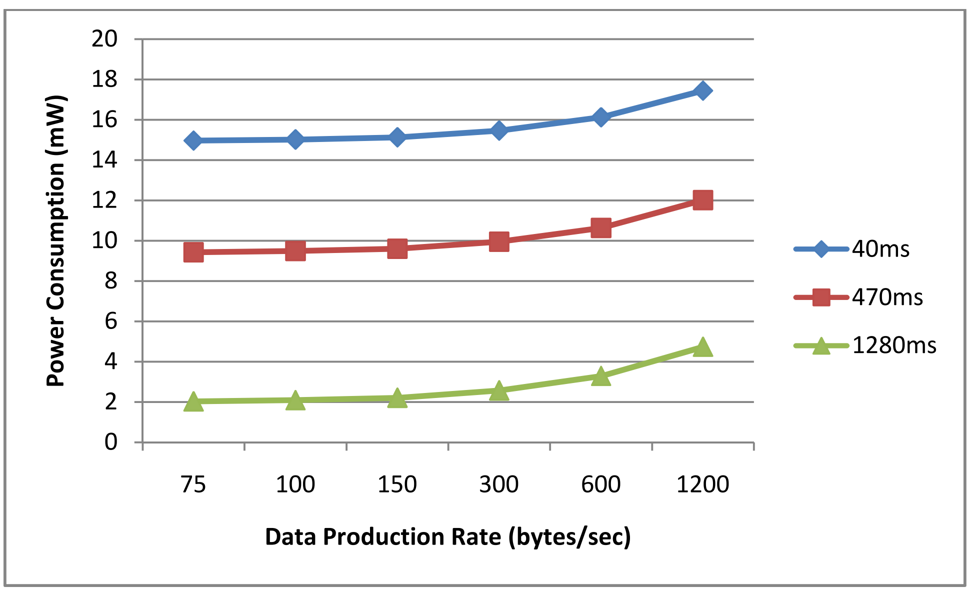

Figure 1: Power consumption vs. data production rate for different sniff intervals and DH3 packet

2 WiFi

WiFi radios have a high wakeup and connection maintenance energy, but low energy per bit transmission cost and high bandwidth. The power consumption models for a WiFi radio are based on the experimental model derived in [Context-for-Wireless] for an HTC Wizard phone. It was discovered that if the WiFi module is left on for more than 15 sec, it is more efficient to shut it down. Thus, we break up our analysis into two parts: for transmission intervals (T_{trans}) less than 15 sec, and those greater than 15 sec. For simplicity, the time taken to transfer data (O(ms)) after each interval is assumed to be negligible as compared to the transmission interval (O(sec)).

Total data collected by the WiFi module in T_{trans} interval: $D_{trans} = d * (T_{trans}/ t_{buf})$ bytes
Energy to transmit D_{trans} bytes at 7 J/MB: $E_{trans} = D_{trans} * 7/(1024 * 1024)$ J
Energy required to maintain the connection for T_{trans} time at 19 J/min: $E_m = 19 * T_{trans}/60$ J
Energy required to establish the connection: $E_e = 5$ J

T_{trans} interval	**Power Consumption** (mW)
$T_{trans} <= 15$ sec	$(E_{trans} + E_m)/T_{trans} = 7000 * f/(1024 * 1024) + 19000/60$ $= 0.0067 * f + 316.67$
$T_{trans} > 15$ sec	$(E_e + E_{trans})/T_{trans} = 5000/T_{trans} + 7000 * f/(1024 * 1024)$ $= 5000/T_{trans} + 0.0067 * f$

Table 5: Power consumption models for different transmission intervals for a WiFi radio

T_{trans} (sec)	**Data Production Rate** (bytes/sec)					
	75	**100**	**150**	**300**	**600**	**1200**
	Power Consumption (mW)					
T_{trans}<=15	317.1725	317.34	317.675	318.68	320.69	324.71
30	167.1692	167.3367	167.6717	168.6767	170.6867	174.7067
60	83.83583	84.00333	84.33833	85.34333	87.35333	91.37333
120	42.16917	42.33667	42.67167	43.67667	45.68667	49.70667
300	17.16917	17.33667	17.67167	18.67667	20.68667	24.70667
600	8.835833	9.003333	9.338333	10.34333	12.35333	16.37333
1200	4.669167	4.836667	5.171667	6.176667	8.186667	12.20667

Table 6: Power consumption of a WiFi radio at different data production rates and different transmission intervals

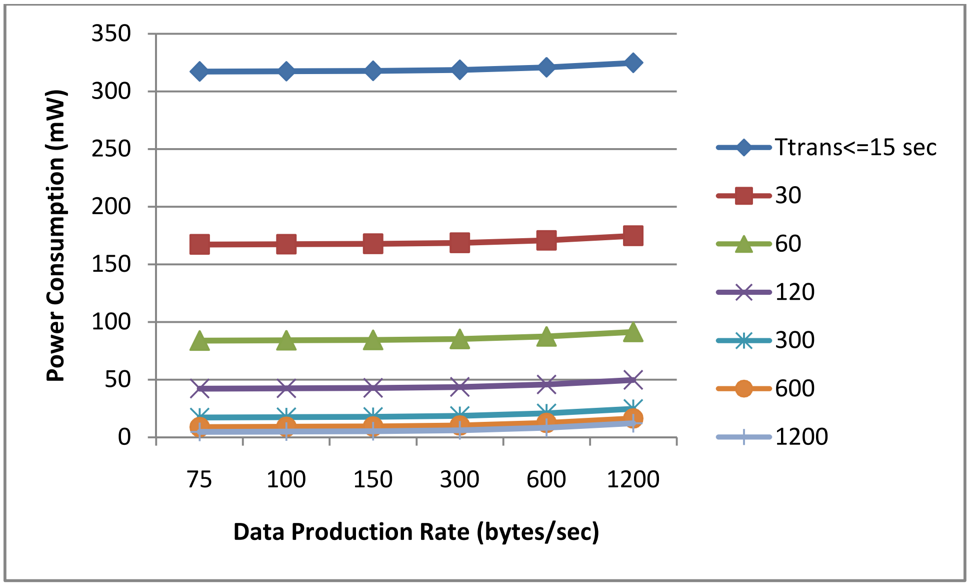

Figure 2: Power consumption of a WiFi radio (HTC wizard phone) for different data production rates and transmission intervals (T_{trans})

3 GSM/EDGE

Cellular radios have low connection maintenance energy, but high energy per bit transmission cost and low bandwidth. The power consumption models for a GSM/EDGE radio are based on the experimental model derived in [Context-for-Wireless] for an HTC Wizard phone. For simplicity, the time taken to transfer data (O(ms)) after each interval is assumed to be negligible as compared to the transmission interval (O(sec)). Thus, from the analysis given below, we observe that for small data transfers that satisfy the above assumption, power consumption is dependent only on the data production rate. Moreover, figure 3 shows that lowering the data production rate has a great impact on reducing the power consumption.

Total data collected by the EDGE module in T_{trans} interval: $D_{trans} = d * (T_{trans}/ t_{buf})$ bytes
Energy to transmit D_{trans} bytes at 95 J/MB: $E_{trans} = D_{trans} * 95/(1024 * 1024)$ J
Energy required to maintain the connection for T_{trans} time at 1.2 J/min: $E_m = 1.2 * T_{trans}/60$ J

Power consumption = $(E_m + E_{trans})/T_{trans} = 1200/60 + 95000 * f/(1024 * 1024)$ mW

Thus, **Power consumption** = 20 + (0.0905 * f) mW

Data Production Rate (bytes/sec)	75	100	150	300	600	1200
Power consumption (mW)	26.7875	29.05	33.575	47.15	74.3	128.6

Table 7: Power consumption for a GSM/EDGE radio corresponding to figure 3

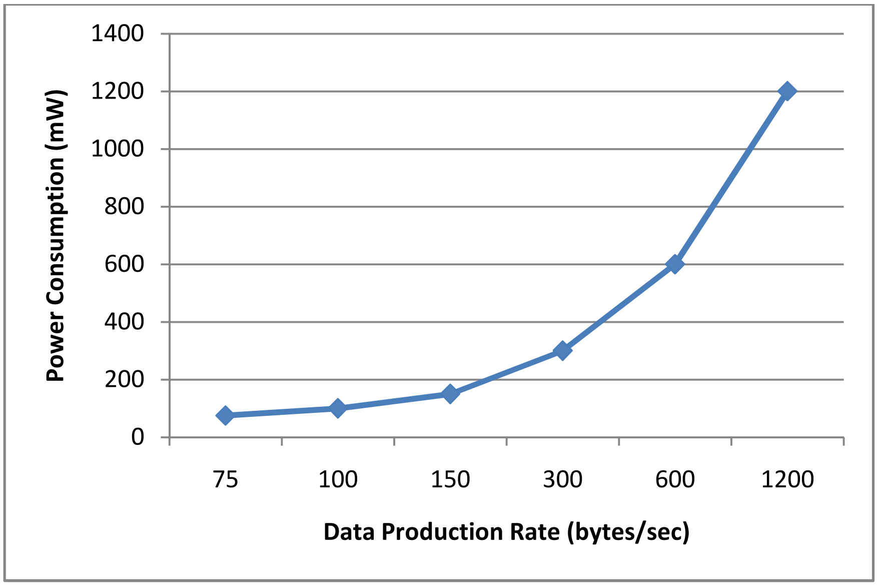

Figure 3: Power consumption for a GSM/EDGE radio for different data production rates