

The Energy-per-Useful-Bit Metric for Evaluating and Optimizing Sensor Network Physical Layers

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Abstract- To become truly ubiquitous, sensor network nodes must achieve ultra low power consumption. This paper proposes the Energy-per-Useful-Bit (EPUB) metric for evaluating and comparing sensor network physical layers. EPUB includes the energy consumption of both the transmitter and receiver, and amortizes the energy consumption during the synchronization preamble over the number of data bits in the packet. Using EPUB, we compare six existing sensor network PHYs. Next, we optimize the PHY according to EPUB. We conclude that the EPUB of sensor network PHYs can be reduced by increasing data rate, lowering carrier frequency, and using simple modulation schemes such as OOK to reduce synchronization overhead.

I. INTRODUCTION

Sensor network research is aimed at enabling a richer experience of sensing, monitoring, and effecting our environment. The ubiquitous deployment of hundreds – or thousands – of nodes makes changing batteries prohibitive. Therefore, they must be energy-self contained either by lasting their lifetime on a single battery charge, or by scavenging energy from the environment. Average power consumption is, therefore, a primary metric of sensor networks (for instance, a goal of 100 μ W at a size of 1cm³ for indoor environmental monitoring [1]). Since energy scavenging and energy storage components dominate node size [1], lowering the power consumption also lowers size and cost.

This paper focuses on physical layers (PHYs) for ad-hoc wireless sensor networks (WSNs). We assume that nodes discover each other and self-organize into a reliable communication network. To this end, we assume peer-to-peer communication between any pair of neighboring nodes. Therefore, we consider the entire link, with transmitter and receiver power included. As is typical of packet-based networks like 802.11, Bluetooth, and 802.15.4 (ZigBee), we assume a preamble is included at the front of every packet to enable PHY layer synchronization (timing recovery, channel estimation, etc.).

This paper proposes the Energy-per-Useful-Bit (EPUB) metric for evaluating and optimizing WSN PHYs. Although standardized radios, such as 802.15.4, exist for WSNs, there is also active research in custom

PHYs [2]-[8] spanning a wide range of carrier frequencies, data rates, and modulation schemes. A metric for WSN PHYs enables meaningful comparison and optimization of the custom PHYs and can direct future WSN PHY standards. If selecting amongst existing PHYs for a given system, designers can use this metric to choose the lowest energy radio for their particular application (given MAC scheme, expected packet lengths, transmit distances, and required BER).

The EPUB metric is introduced in Section II. A comparison of six existing WSN PHYs is made in Section III. In Section I, the PHY layer design space is considered, including modulation, data rate, carrier frequency, and synchronization overhead to determine the proper trade-offs for EPUB reduction. Finally, in Section V, other considerations for PHY implementations are discussed.

II. THE ENERGY PER USEFUL BIT METRIC

We introduce the Energy-per-Useful-Bit (EPUB) of a PHY as:

$$EPUB = \left(\frac{B_D + B_P}{B_D} \right) (P_{TX} + \xi \cdot P_{RX}) T \quad (1)$$

where B_D and B_P are respectively the average number of data and preamble bits in a packet, T is the bit time in seconds, P_{TX} is the power of the transmitter in mW, and P_{RX} is the power of the receiver in mW including the analog-to-digital converter (ADC) and synchronization circuitry. The constant ξ is determined by the MAC scheme and represents the average proportion of time spent in receive mode (ρ_{RX}) divided by that spent in transmit mode (ρ_{TX}). These parameters are readily available from MAC layer simulation and analysis [9].

In the context of WSNs, optimal node implementation is application dependent. For instance, the choice of MAC layer depends on many factors including the volume and predictability of the application's traffic patterns. Different MACs will in turn favor different PHY implementations. Hence, the chosen metric, EPUB, enables a comparison of PHYs within the context of a network scenario, with the same channel model, average transmit distance, BER, and MAC scheme (ξ). We stress the importance of using the EPUB metric as opposed to others (e.g. unweighted average power or energy [10][11]) because it accounts for the synchronization costs (both the circuit energy

and the additional preamble bits that are sent) and weights the transmitter and receiver in proportion to their relative usage. Note that the EPUB metric compares systems with the same uncoded BER. Once a coding scheme has been selected, it can be applied equally to all systems under consideration.

In the following subsections, we break EPUB down into two components,

$$E_{TOT} = (P_{TX} + \xi \cdot P_{RX})T \quad (2)$$

which represents the asymptotic behavior of EPUB for long packets where preamble overhead no longer matters, and

$$preamble\ overhead = \left(\frac{B_D + B_P}{B_D} \right). \quad (3)$$

III. COMPARISON OF EXISTING RADIOS

In this section, six existing radios under consideration for WSN applications are compared using the EPUB metric. Table 1 details the radios' salient parameters. This comprehensive set spans a range of data rates, modulation schemes, and carrier frequencies. They include:

- PNII – A low power direct conversion transceiver with data rates and modulation schemes similar to 802.11b
- PN3 TR – An OOK radio using a tuned resonator and envelope detector optimized for low data rates
- PN3 SR and Favre SR – two super regenerative radios targeted at low data rate applications
- Molnar – a low power FSK radio targeted at low data rate applications
- Chipcon Zigbee (CC2420) – a commercially available Zigbee (802.15.4) radio

For this comparison, we assume a 10m range, a BER of 10^{-4} , $\xi=1$, and a path loss of:

$$L_P(dB) = 20 \cdot \log_{10}(f_c) + 30 \cdot \log_{10}(d) - 13 \quad (4)$$

where f_c is the carrier frequency in MHz and d is the distance in meters.

Some of these radios are designed to transmit higher output power levels than that required for the assumed 10 m range. For those cases, the required output power is calculated based on the receiver sensitivity and the path loss. Then, transmitter power consumption is recalculated based on the radio's power amplifier efficiency.

Several notable radios have been omitted. The WiseNet [8] radio, expected to achieve an excellent EPUB metric, could not be included due to insufficient information. Among standards-based radios, Bluetooth has been supplanted for WSNs by 802.15.4, which was specifically designed for these types of applications. Widely used commercially available nodes by Crossbow currently use the Chipcon CC2420 2.4 GHz Zigbee radio (compared above) or the Chipcon CC1020, which operates in the 400 and 900 MHz range.

The six example radios are compared in Figure 1 where EPUB is plotted vs. packet length, at typical packet lengths for WSN applications. EPUB is a strong function of packet length when preambles are long. Section IV discusses methods of preamble reduction. Aggregation of multiple packets results in EPUB reduction by amortizing the preamble over more data bits.

The PN3 TR and Chipcon Zigbee radios have considerably higher EPUB than the others. Amongst the remaining four, the PN3 SR and Favre SR radios perform the best.

Table 1: Specifications for radios under consideration

		PNII [2]	PN3 TR [3]	PN3 SR [4]	Favre SR [5]	Chipcon Zigbee [6]	Molnar [7]
Modulation		DSSS - DQPSK	OOK	OOK	OOK	DSSS-OQPSK	FSK
Carrier Frequency	(MHz)	2400	1900	1900	900	2400	900
Sensitivity @ given data rate	(dBm)	-84.2	-78	-101	-95	-94	-94
Required Transmitted Power @10 m	(dBm)	-1.2	5	-19.5	-18	-11	-18
P_{TX} (at above output power)	(mW)	33	9.3	0.3	0.3	20	0.5
P_{RX}	(mW)	70	3	0.4	3.75	35.5	1.2
Data Rate	(kbps)	1600	50	20	100	250	20
Header Length	(symbols)	8	18	28	18	32	8
E_{TOT}	(pJ)	67	405	42	47	221	94

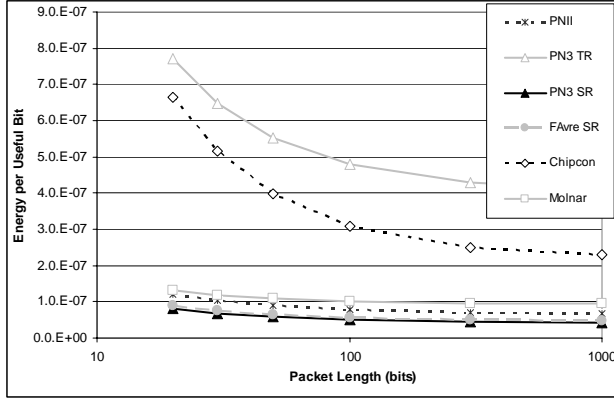


Figure 1: EPUB vs. packet length for the six radios under consideration

IV. OPTIMIZATION OF PHYSICAL LAYER

Typical optimization for PHY layer power reduction generally focuses on circuits and architectures for a given modulation scheme, carrier frequency, data rate, etc. Here, we take a step back and examine models for modulation scheme, carrier frequency, and data rate to suggest suitable choices for reducing EPUB. The first two subsections examine the effects of data rate and carrier frequency on E_{TOT} . The third subsection examines the effect of modulation scheme and data rate on preamble overhead.

Although optimization of data radios for energy-constrained networks has been carefully studied in [11], the general findings can be misleading when applied to WSNs. Given a fixed bandwidth, maximum transmission time, maximum peak power, and number of bits to be transmitted, [11] optimizes energy consumption of the transceiver for MQAM and MFSK. However, OOK modulation has been omitted, which can have a dramatically simplified radio front-end resulting in faster turn-on times and better RX efficiency in terms of energy per bit [3][4]. For systems like WSNs that are not transmit power dominated, [11] shows that higher order modulation constellations can result in lower energy consumption if there is a bandwidth constraint. However, the increased synchronization costs of higher-order modulation schemes, which have been shown to be dominant for short packet systems [12], are not included in [11]’s analysis. In addition, the bandwidth constraint is not necessary when the data rates in use result in lower bandwidth than the mandated limit even with low modulation constellations.

Change in E_{TOT} vs. data rate

In this section, the effect of data rate on E_{TOT} is evaluated. Since E_{TOT} includes both the power consumption of the transmitter and receiver, we derive

models for each vs. data rate. The transmitter and receiver together have to overcome the path loss, L_P , in the channel. We model this link budget as in [13] as

$$P_{RAD}(dBm) \geq L_P(dB) + L_R(dBm) + L_S(dB) + SNR(dB) \quad (5)$$

where P_{RAD} is the radiated power from the transmitter, L_R is the receiver front-end noise power, L_S is the SNR loss due to synchronization parameter estimation variance, and SNR is the required SNR at the decision device in order to achieve the necessary BER.

In our equations, path loss is generally left as a variable so that an appropriate model can be used. However, to illustrate our examples, (4) is used.

The front-end noise power is dependent on data rate, and can be written in terms of the equivalent “noise temperature,” φ_n , of the front-end [13] as

$$L_R(dBm) = 10 \cdot \log_{10}(k \cdot \varphi_n \cdot W) + 30 \quad (6)$$

where W is the receiver bandwidth in Hz, k is Boltzmann’s constant (1.3807×10^{-23} J/K), and 30 dB denominates the power consumption in mW. For a fixed modulation scheme, the bandwidth, W , scales inversely with the bit time, T . A decrease in T incurs an increase in noise power. Balancing the link budget requires some combination of increasing P_{RAD} and decreasing φ_n . Intuitively, the compromise between these two will depend on the relative efficiency of the transmitter to changes in P_{RAD} vs. efficiency of the receiver to changes in φ_n . We derive the specific tradeoff below.

Power consumption of the transmitter and receiver are generally complex functions of the data rate. However, within a small window around the original design, transmitter and receiver performance and power consumption can be linearized with respect to data rate. With this simplified model, the first order effects of data rate on EPUB can be examined.

To first order, path loss, SNR loss due to synchronization, and required SNR are, invariant to data rate. Power consumption of the transmitter is, to first order, independent of data rate, and only depends on radiated power. As in [10], we linearize as

$$P_{TX} = \alpha_{TX} + \beta_{TX} P_{RAD} \text{ (mW)} \quad (7)$$

where $1/\beta_{TX}$ is defined as the marginal efficiency of the transmitter, and α_{TX} is a linearization constant.

Power consumption of the receiver includes that in the front-end and synchronizer. Front-end power is

dependent on φ_n^\dagger whereas synchronizer power consumption (including the ADC) is to first-order proportional to data-rate since the clock rate of the synchronizer is most often a constant multiple of the data-rate. Therefore, we linearize receiver power consumption as:

$$P_{RX} = \alpha_{RX} + \beta_{RX} / \varphi_n + \beta_{SYNC} / T \text{ (mW)} \quad (8)$$

where $1/\beta_{RX}$ is defined as the marginal efficiency of the transmitter, and β_{SYNC} and α_{RX} are linearization constants.

Finally, the total energy consumption per bit of the transmitter and receiver can be written as

$$E_{TOT} = (\alpha_{TX} + \beta_{TX} P_{RAD} + \xi \alpha_{RX} + \xi \beta_{RX} / \varphi_n + \xi \beta_{SYNC} / T) T \quad (9)$$

Direct inspection of (9) reveals that E_{TOT} is minimized when T is minimized. Therefore, to first order, faster data rates minimize EPUB. Including second order effects would show that β_{TX} , β_{RX} , and β_{SYNC} are not constant, but generally increasing functions of T . As data rate is increased, the front-end architectures must accommodate higher bandwidths resulting in lower transmit and receive efficiencies. As will be discussed in a following subsection, an increase in sync functionality may be needed to accommodate higher data rates. This increasing overhead with higher data rates puts a damper on increasing energy efficiency. Therefore, there is an optimal data rate $T > 0$ for a given process technology where increases in data are equally tempered by decreases in efficiencies. Finding this optimal data rate requires better modeling of the analog front-end and synchronization system performance vs. power consumption. These problems are the domain of ongoing research in analog CAD and synchronization.

Substituting (5) and (6) into (9) and taking the derivative w.r.t. P_{RAD} , we get a minimum E_{TOT} when

$$P_{RAD} = \sqrt{\frac{\beta_{RX}}{\beta_{TX}} (\xi \cdot W \cdot k \cdot 10^3 \cdot 10^{(L_p + L_s + SNR)/10})} \quad (10)$$

(mW).

[†] RF circuits historically operated in strong inversion where noise is proportional to the inverse transconductance (for transistors acting as gain stages), and transconductance is proportional to the square root of the current through the device. Recently, transistors for RF applications are more often being biased in weak inversion where transconductance is proportional to current [14]. Regardless of the biasing regime, power consumption can be linearized around a given design point.

Equation (10) dictates that P_{RAD} should balance the efficiencies of the transmitter and receiver (β_{RX}/β_{TX}) as intuition indicates.

Figure 2 shows EPUB vs. data rate for the PN3 SR transceiver with P_{RAD} selected according to (10), and $\xi=1$. The original design point is also shown in the plot. The linear model of this radio is valid for data rates of approximately 20 to 100 Kbps. Even when choosing a non-optimal data rate, using (10) to choose the optimal transmit power and receiver sensitivity can still yield significant reductions in EPUB. Given the optimal ratio of transmit power and receive sensitivity, there is over a factor of 2 decrease in EPUB in going from 20 Kbps to 100 Kbps. The design point of 100 Kbps is quite reasonable for this radio as the required transmit power of -10 dBm is well below the FCC limits in the 2.4 GHz ISM band. The required sensitivity for 100 Kbps operation is -93 dBm at an estimated receiver power consumption of 318 uW.

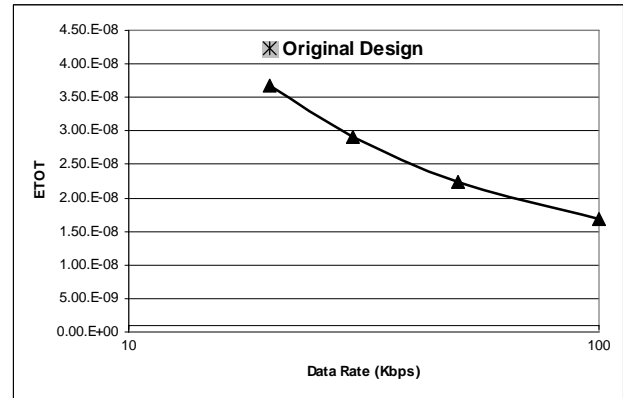


Figure 2: E_{TOT} vs. data rate for the PN3 SR radio

Change in E_{TOT} vs. carrier frequency

Carrier frequency is an important choice for WSNs. Heavily influenced by government regulation, WSNs in the U.S. have generally been constrained to the ISM bands of 400 MHz, 900 MHz, 2.4 GHz, and 5 GHz. Our goal is to explore the ideal radio characteristics for WSNs, so for the moment, the following discussion proceeds independently of the government regulations.

Deciding the optimal carrier frequency requires models of how the node power, size and cost scale with carrier frequency. Power consumption of baseband circuits (ADC and synchronizer), are independent of the carrier frequency because they operate on the signal after down-conversion from the carrier. Only the front-end circuits scale with frequency. Therefore, we modify equation (9) by making β_{TX} , β_{RX} , α_{RX} , α_{TX} arbitrary functions of the carrier frequency, f_c :

$$E_{TOT} = \left(\begin{array}{l} \alpha_{TX}(f_c) + \beta_{TX}(f_c) \cdot P_{RAD} + \\ \alpha_{RX}(f_c) + \beta_{RX}(f_c) / \varphi_n + \beta_{SYNC} / T \end{array} \right) T. \quad (11)$$

Although the exact relationship changes for different radio front-ends, it is well accepted to be between linear and quadratic [14]. Not included here are secondary effects regarding integrated passives. The quality factor (Q) of some passive devices improves with higher carrier frequency. Additionally, higher carrier frequencies allow smaller passives that are more easily integrated with low parasitics on-chip. Lower parasitics and higher Q result in lower power consumption.

We also modify the link budget in equation (5) to include the frequency-dependent effects of antenna gain:

$$P_{RAD}' \geq L_P + L_R + L_S + SNR - 10 \cdot \log_{10}(G_{TX}G_{RX}) \quad (12)$$

where G_{TX} and G_{RX} are the gain of the transmit and receive antennas respectively). Note that the path loss, as we model it, increases with f_c^2 . We model antenna gain as in [13] as:

$$G = 4\pi A \eta / \lambda^2 \quad (13)$$

where A is the antenna capture area, η is an efficiency constant, and λ is the wavelength, which is inversely proportional to f_c . Systems with lower carrier frequencies can either use a larger antenna, or incur a quadratically lower antenna gain.

Figure 3 plots E_{TOT} vs. f_c for four scenarios: 1) front-end power scales linearly with f_c , antenna gain is fixed, 2) front-end power scales quadratically, antenna gain is fixed, 3) front-end scales linearly, antenna area is fixed, and 4) front-end scales quadratically, antenna area is fixed. For each data point, P_{RAD} is selected as in (10). In all cases, lower carrier frequencies result in lower energy consumption, with scenario 3 showing only a weak dependence. For the PN3 SR radio, under scenario 2, going from a carrier frequency of 2.4 GHz to 900 MHz could reduce E_{TOT} by a factor of 3.

The size of the communication component of WSN nodes is usually smaller at higher carrier frequencies because of smaller, more integrated, passives. However, today's nodes are not limited in volume by the communication component; they are limited by the energy scavenging and other power train components [1]. Even scenarios 1 and 2 above, with larger antennas at lower carrier frequencies, may result in smaller node size because a smaller power train can be used. Scenarios 3 and 4, where antenna size is fixed, will definitely result in a smaller node at lower carrier frequencies as long as the larger passives can be managed.

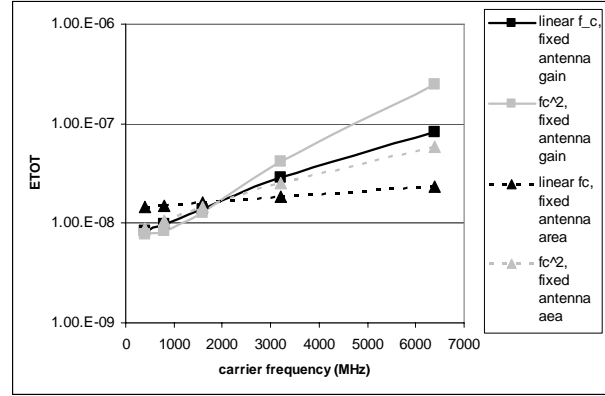


Figure 3: E_{TOT} vs. carrier frequency

Cost can be a mitigating factor in decreasing carrier frequency if passives that can be integrated for higher carrier frequencies cannot be integrated at lower carrier frequencies. Off chip passives increase node costs through the cost of the passives themselves and the increase in circuit board area. Even when integrated on chip, lower frequency passives require more area, and hence increase silicon cost.

We demonstrated that lower carrier frequencies are better for WSNs as long as the size and cost of the passives can be managed.

Synchronization considerations

The synchronization overhead, represented in EPUB by $(B_D + B_P)/B_D$, is only beginning to be addressed [12]. WSN traffic is comprised of short packets. Control packets of 30 bits and data packets of 200 bits on average are typical of a WSN for indoor environmental sensing, with an average data rate of 10 Kbps, and using a pseudo-synchronous MAC [9]. For reference, the 32-bit preamble specified in 802.15.4 imposes greater than 100% overhead on control packets. Therefore, it is important that the receivers have fast turn-on times. Long oscillator lock times and slow AGC loops lead to longer preambles. Fast oscillator turn-on times can be achieved [3][4] that are negligible compared to the symbol period. With very short packets, EPUB can be reduced more significantly by affecting a reduction in packet overhead than in transceiver power consumption. That is, we can reduce EPUB by paying a higher E_{TOT} to get a lower sync overhead. One such example is the trend toward simple modulation schemes.

Although simpler modulation schemes typically increase E_{TOT} , they allow a shorter sync preamble. It has been shown [2] that differentially coherent modulation schemes have a lower EPUB than coherent modulation schemes for this reason. Fully non-coherent modulation schemes (such as OOK or non-coherently demodulated FSK) have even lower

synchronization requirements and simultaneously simplify the front-end [3][4]. We found only a minor difference in EPUB between using OOK or FSK modulation for the PN3 SR radio.

The impact on synchronization of channel impairments such as delay spread and coherence time and transceiver impairments such as clock and carrier reference offsets can be addressed at the system level for overall EPUB reduction [12]. One such example is using accurate enough frequency references so that timing can be estimated once during the packet, rather than tracked throughout the entire packet. Another example is choosing data rate to simplify synchronization. Packets longer than the coherence time of the channel require re-estimation or tracking. Data rates greater than 100 Kbps allow 1000-bit packets to be sent before the 90% coherence time for indoor office environments at 2.4 GHz. On the other hand, data rates slower than 200 Kbps reduce multipath effects to a negligible level so that equalization can be avoided. Therefore, for a system in the 2.4 GHz band that needs to send 1000-bit packets, data rates between 100 Kbps and 200 Kbps greatly simplify the synchronization requirements [12].

We conclude that simple modulation schemes and system-level considerations can reduce the sync overhead for EPUB minimization.

V. OTHER CONSIDERATIONS

There are considerations for WSNs beyond those discussed in this paper. Most notably, FCC compliance may significantly direct the choice of MAC and PHY design away from the optimal points. Interference will most likely be a significant factor for deployed WSNs. Of particular importance will be coexistence with other widely used wireless protocols such as 802.11abg, Bluetooth, 802.15.4, and UWB.

VI. CONCLUSION

In this work, we proposed the EPUB metric for comparing and optimizing wireless sensor network PHY layers. Significantly suboptimal energy consumption could result from using other metrics that exclude synchronization costs or use an unweighted average of transmitter and receiver power consumption. The EPUB metric enables comparison of PHYs with different carrier frequencies, modulation schemes and data rates. An optimization showed that greater than 2x reduction in EPUB is possible by increasing data rate, a 3x reduction by lowering carrier frequency, and further reduction for short packets by using simple modulation schemes to reduce synchronization overhead.

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