A Realistic Power Consumption Model for Wireless Sensor Network Devices

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Abstract-- A realistic power consumption model of wireless communication subsystems typically used in many sensor network node devices is presented. Simple power consumption models for major components are individually identified, and the effective transmission range of a sensor node is modeled by the output power of the transmitting power amplifier, sensitivity of the receiving low noise amplifier, and RF environment. Using this basic model, conditions for minimum sensor network power consumption are derived for communication of sensor data from a source device to a destination node. Power consumption model parameters are extracted for two types of wireless sensor nodes that are widely used and commercially available. For typical hardware configurations and RF environments, it is shown that whenever single hop routing is possible it is almost always more power efficient than multi-hop routing. Further consideration of communication protocol overhead also shows that single hop routing will be more power efficient compared to multi-hop routing under realistic circumstances. This power consumption model can be used to guide design choices at many different layers of the design space including, topology design, node placement, energy efficient routing schemes, power management and the hardware design of future wireless sensor network devices.

I INTRODUTION

A wireless sensor network (WSN) consists of a large number of sensor nodes. Characteristically, a sensor node includes a processor, wireless radio and various sensors. Within a WSN, nodes collaborate amongst themselves to accomplish a common task. Because sensor nodes are usually battery-powered and operate unattended for relatively long periods of time, maximizing the overall energy efficiency of a WSN is very critical.

Over the last few years, some researchers [23] have claimed that multi-hop network implementations consume less energy than an equivalent single-hop network. Conversely, other researchers [1] [4] [11] argue that single-hop implementations consume less energy in relaying data compared to equivalent multi-hop networks due to simpler routing protocols, lower communication overhead, and higher overall efficiency. Nearly all aspects of proper WSN design from low level hardware design to high level communication protocols depend on understanding the power consumption characteristics of sensor nodes and quantifying the necessary conditions and criteria for selecting single-hop versus multi-hop network schemes.

Recent analyses of WSN energy efficiency have been widely based on a sensor node power consumption model [3] [19] where the impact of the sensor node device hardware (which can be improved) and external radio environment (which is largely uncontrollable) are lumped together. However, by using a more realistic power consumption model of the communication subsystem which clearly separates the power consumption of each hardware component and the impact of the external radio environment, we have been able to derive clearer results which provide insight into which hardware components are limiting WSN performance and when multi-hop and single-hop networks should be used.

Power consumption measurements of the communication subsystem of sensor node devices reveal clear discrepancies between widely cited power consumption models and actual characteristics of real hardware implementations. For example, the measured power consumption of the receiving circuitry is often greater than the power consumption of the transmitting circuitry [6][15][16]. Similarly, the power consumption for baseband digital signal processing is found to be comparable to the power consumption of the combined transmit and receive circuitry [7]. Furthermore, an accurate power consumption model should be able to accurately reflect the impact of recent advances in high efficiency power amplifiers for WSN applications [12][13].

In this paper, we develop a realistic power consumption model for WSN devices by incorporating the characteristics of a typical low power transceiver. We then compare single-hop and multi-hop routing schemes based on the power consumption model.

The remainder of the paper is organized as follows:

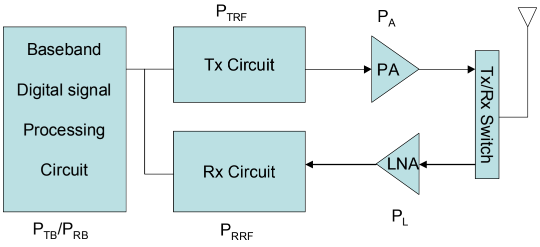
in Section II, we propose a realistic power consumption model for wireless sensor network devices. In Section III, we describe the upper limit of energy efficient communication based on transmit power and distance, derive a necessary condition for energy efficient data transmission in wireless sensor networks, and give energy efficiency criteria for selecting hoping scheme. In Section IV, we present real examples to illustrate the analysis in the previous section. In Section V, we analyze the impact of protocol overhead for multi-hop routing schemes on the overall energy efficiency of the network. In Section VI, we discuss some potential applications, which incorporate our power model and selection criterion. In Section VII we describe related work. Section VIII concludes the paper.

II POWER CONSUMPTION MODEL

In this section, we derive a power consumption model for the communication subsystem of a wireless sensor network device. For this model, the physical communication rate is constant and assumed to be *B* bits per second. In addition, we initially assume the communication bandwidth is low enough that interference and transmissions collisions can be easily avoided by using simple protocols without significant power consumption penalty.

A. Power Consumption of Communication Module

Figure 1 illustrates the internal structure of a communication module found in a typical WSN node, and defines the power consumption of each component.



P_{TB}/P_{RB}: Power consumption in baseband DSP circuit for transmitting or receiving (mW)
P_{TRF}/P_{RRF}: Power consumption in front-end circuit for transmitting or receiving (mW)
P_A: Powerr consumption of PA for transmitting (mW).
P_L: Power consumption of LNA for receiving (mW)

Fig.1 Communication Module Structure

Based on the structure and power consumption of each component, the total power consumption for transmitting and for receiving, denoted by P_T and P_R, are specifically given by:

$$P_T(d) = P_{TB} + P_{TRF} + P_A(d) = P_{T0} + P_A(d)$$
$$P_R = P_{RB} + P_{RRF} + P_L = P_{R0}$$

Where $P_A(d)$ is the power consumption of the power amplifier which is a function of the transmission range, *d*. Since P_{TB} and P_{TRF} do not depend on the transmission range, the two components can be modeled as a constant, P_{T0}. Similarly, the power consumption of the receiving circuitry can be modeled as a constant, P_{RO}, since P_{RB} and P_{RRF} are clearly not dependent on transmission range, and P_L is also a constant while assuming that the LNA is properly designed and biased to provide the necessary sensitivity to reliably receive, demodulate and decode a minimum power signal, $P_{Rx\text{-}min}$.

While there are many types of RF power amplifiers, the total power consumption of a power amplifier, $P_A(d)$, will depend on many factors including the specific hardware implementation, DC bias condition, load characteristics, operating frequency and PA output power, P_{Tx} [14]. A simple class A power amplifier is shown in Figure 2 with a simple resistive load, R_L.

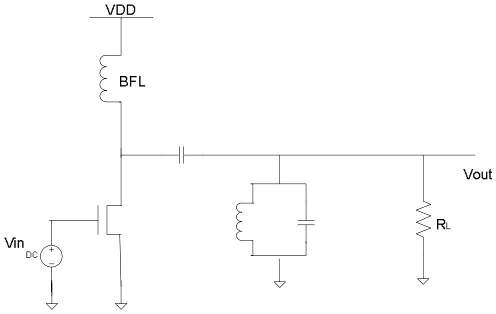


Fig. 2 Simple class A power amplifier circuit

The power amplifier delivers RF output power, P_{Tx}, to the antenna/load. In general, the required RF output power, $P_{Tx}(d)$ for reliable transmission will depend on the transmission range, *d*. The large inductance, BFL, feeds DC power to the drain of the transistor. The total power consumption of the PA is given by P_{DC} and is the same as P_A defined above. The ratio of RF output power to DC input power is called the drain efficiency (denoted as η) and is given by:

$$\eta = \frac{P_{Tx}}{P_{DC}}$$

By definition, the drain efficiency of a PA will be less than 100%. For example, simple class A power amplifiers have a maximum drain efficiency of 50% as equal amounts of power are dissipated in the bias circuitry and in the load. The drain efficiency will typically vary when the output power delivered to the load changes. In particular, for most types of power amplifiers, the drain efficiency increases while P_{Tx} is increasing and reaches its maximum value when P_{Tx} reaches the maximum output power, P_{max} [12].

By combining the concept of drain efficiency with the formula described in the previous part of this section, the power consumption of the communication module can be modeled as:

$$P_T(d) = P_{T0} + P_{Tx}(d)/\eta \qquad (2\text{-}1)$$
$$P_R = P_{R0}$$

B. Channel Model

The RF environment and communication channel are simply modeled by only considering path loss [2] and by ignoring fading, multi-path and other more complex effects. Thus,

$$P_{Rx} = P_{Tx}/(A \times d^{\alpha}) \qquad (2\text{-}2)$$

Where P_{Tx} is RF power delivered to the antenna by the PA of the transmitting sensor node and P_{Rx} will be the RF power received by the antenna of receiving sensor node and delivered to the LNA. The parameter A is determined by characteristics of the transmitting and receiving antennas. The path loss exponent is given by α and is about 2 for freespace and will increase due to the presence of obstacles.

C. Basic Power Consumption Model

Combining equations (2-1) and (2-2), we can determine the power consumption of the communication module for a given radio environment as follows:

$$P_T(d) = P_{T0} + \frac{P_{Rx} \times A \times d^{\alpha}}{\eta}$$

The SINR (Single-to-Interference and Noise-Ratio) requirements of the receiver determine the minimum required received power, $P_{Rx\text{-}min}$, for reliable communication. Thus, the minimum power consumption to reliably transmit data to another sensor node which is located at a distance, d, is given by:

$$P_T(d) = P_{T0} + \frac{\varepsilon \times d^{\alpha}}{\eta} \qquad (2\text{-}3)$$

Where ε is a constant given by $P_{Rx-\min} \times A$. Similarly, the power consumption of a sensor node to reliably receive data is a constant and is given by:

$$P_R = P_{R0}$$

D. Multi-hop Power Consumption Model

In order to evaluate the power consumption model for a multi-hop network, a network model is needed. If we assume a channel model, which only includes path loss then a multi-hop routing scheme will perform the best in a simple 1-D linear WSN topology [2]. The single-hop 1-D linear WSN consists of a source node S and a destination node D separated by a distance R, and multi-hop 1-D linear WSN has an additional n-1 intermediate identical relay nodes N_i, $i=1, \ldots n-1$, placed in a line from S to D (see Figure 3). In Figure 3(b), the relay nodes are placed an arbitrary distance apart, and in Figure 3(c) the relay nodes are placed equidistantly. The objective of the WSN is the reliable delivery of the data generated at source node to the destination node.

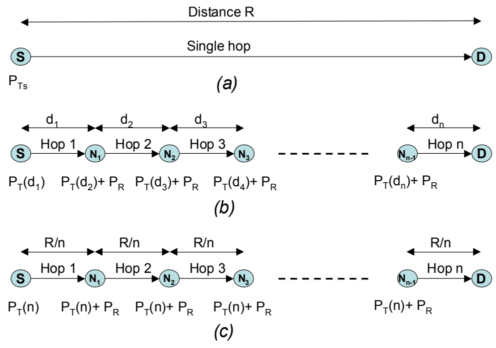


Fig.3 Network Model

P_R describes the power consumption for receiving. $P_T(d_i)$ denotes the power consumption for transmitting over a distance d. i is an integer from 1 to the total number of hops, n. $P_T(R/n)$ denotes power consumption for transmitting over a distance R/n. We use $P(n)$ to denote the total power consumption for sending from S to D with n-hops. We ignore the power consumption in the destination node D, because it is assumed to be connected to an external power supply and is not resourced constrained. Based on the network model in Figure 3(b) and equation (2-3), we can obtain the multi-hop power consumption model with arbitrary distance between nodes as follows:

$$P(n) = (n-1)P_{R0} + nP_{T0} + \frac{\varepsilon}{\eta}\sum_{i=1}^{n} d_i^{\alpha} \qquad (2\text{-}4)$$

Similarly, based on the network model in Figure 3(c), we can obtain the multi-hop power consumption model with equal distance between nodes as follows:

$$P(n) = (n-1)P_{R0} + nP_{T0} + \frac{n \times \varepsilon \times (R/n)^{\alpha}}{\eta} \qquad (2\text{-}5)$$

In particular, this model of WSN power consumption clearly shows the dependence of the power amplifier performance (i.e. drain efficiency, η), which differs from other power consumption models widely cited by the WSN research community.

III CRITERION FOR SELECTING HOPPING SCHEME

Unlike ref. [2], which compared a single-hop scheme with a multi-hop scheme in terms of interference, we focus on the impact of power consumption as the criteria for selecting hopping schemes in this section.

A. Criterion for selecting single hop scheme

Assume P_{max} is the maximum power level of a specific power amplifier, i.e. $0 \le P_{Tx} \le P_{\max}$. The maximum radio range, denoted as R_{max}, is the maximum distance reachable with desired reliability with a transmit power of P_{max}. For this work we denote the distance from source to destination as *R* and is assumed to be $R \le R_{\max}$.

For the 1-D linear network described in Figure 3(c), we first show that the WSN power consumption *P(n)* as defined in (2-5) has the property that *P(1)<P(k)* for all integers *k > 2* if *P(1)<P(2)*.

Taking *P(x)* as a continuous function of *P(n)* given by

$$P(x) = (x-1)P_{R0} + xP_{T0} + \frac{x \times \varepsilon \times (R/x)^{\alpha}}{\eta}$$

Then the derivative of *P(x)* is given by

$$P'(x) = (P_{R0} + P_{T0}) - \frac{(\alpha - 1) \times \varepsilon \times R^{\alpha}}{\eta \times x^{\alpha}} = 0$$

Since α > 1 and all other terms are positive, there is only one minimum point in the curve of *P(x)*, denoted as x_0. Thus, if *P(1) < P(2),* there are two possible cases:

case i: $x_0 \le 1$ then *P(1) < P(k)* for integers *k >1,*

case ii: $1 < x_0 \le 2$ then *P(2)<P(k)* for all integers *k>2* and thus *P(1)<P(k)*.

Consequently, if *P(1) < P(2)*, then *P(1) < P(k)* for integers *k >2*. Therefore, comparing the performance of single-hop to multi-hop WSNs can be simplified to the comparison of a single-hop WSN versus a 2-hop WSN. From equation (2-5), the WSN power consumption at the optimal transmitting power level for the single-hop and 2-hop WSNs are given by P(1) and P(2), respectively. Therefore, if single-hop is more efficient than 2-hop, then *P(1)<P(2)* which can be rewritten as

$$P_{T0} + \frac{\varepsilon \times R^{\alpha}}{\eta} \le P_{R0} + 2P_{T0} + \frac{\varepsilon \times R^{\alpha}}{2^{\alpha-1} \times \eta}$$

$$\varepsilon \times R^{\alpha} \le \frac{(P_{R0} + P_{T0}) \times \eta}{(1 - 2^{1-\alpha})}$$

From (2-2), we know $P_{Tx}(R) = \varepsilon \times R^{\alpha}$, thus

$$P_{Tx}(R) \le \frac{(P_{R0} + P_{T0}) \times \eta}{(1 - 2^{1-\alpha})} = \mathrm{P}_{\mathrm{equiv}}$$

$\mathrm{P}_{\mathrm{equiv}}$ is the maximum power that can be consumed by the power amplifier for any single-hop before it becomes more power efficient to use a 2-hop scheme. Therefore as long as the power consumed by the power amplifier for single-hop communication is low enough to satisfy the above condition and does not exceed $\mathrm{P}_{\max}$, then the single-hop scheme will be the more power efficient scheme. Conversely, if the power overhead for receiving (P_{R0}) and retransmitting (P_{T0}) in a multi-hop scheme are low enough, the lower transmission power of multi-hop scheme will result in lower WSN power consumption. In other words, for minimal power consumption the power amplifier power consumption for any single-hop should be limited to:

$$P_{Tx}(R_s) \le \min\left(\frac{(P_{R0} + P_{T0}) \times \eta}{(1 - 2^{1-\alpha})}, P_{\max} \right) \qquad (3\text{-}1)$$

Equivalently, assuming a simple channel model, the range of any single-hop communication link, R_s should be limited to:

$$R_s \le \min\left(\sqrt[\alpha]{\frac{(P_{R0} + P_{T0}) \times \eta}{(1 - 2^{1-\alpha}) \times \varepsilon}}, \sqrt[\alpha]{\frac{P_{\max}}{\varepsilon}} \right) \qquad (3\text{-}2)$$

In the following text, we analyze the impact of the parameters on $\mathrm{P}_{\mathrm{equiv}}$ and R_s. From equation (3-1) we know that the dominant parameters are *α,* for the radio environment, and *η* for the power amplifier. The range of *α* is usually $2 \le \alpha \le 6$. The parameter *η* is a function of the output power. Ref. [14] shows that the drain efficiency *η* of real devices typically increases as the output power of the power amplifier (P_{Tx}) increases up to its designed target output power. In particular, we looked at two different RF modules, the CC1000 [15] and the CC2420 [16], which are widely used by the WSN community, to provide a real world characterization of *η*. Figure 4.1 and Figure 4.2 present an estimation of drain efficiency based on values extracted from datasheets.

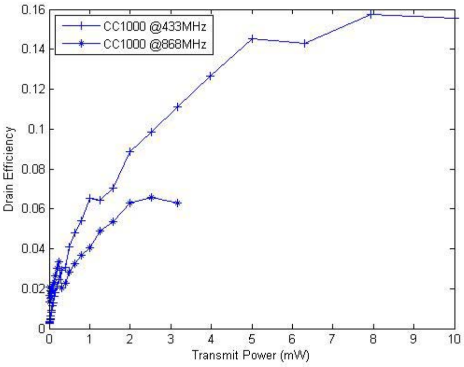


Fig. 4.1. Drain efficiency η vs. transmitting power in CC1000

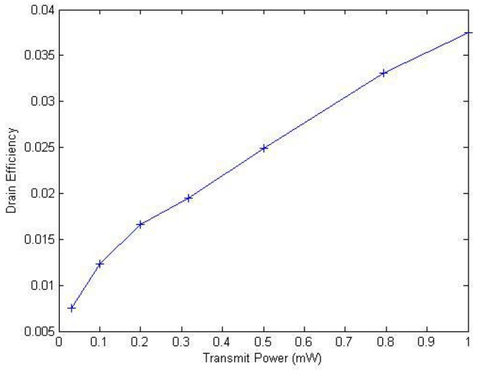


Fig. 4.2. Drain efficiency η vs. transmitting power in CC2420

As illustrated in Figure 4.1 and 4.2, the drain efficiency of the power amplifier in real devices typically improves with higher output power which indicates that better energy efficiency can in general be achieved by maximizing transmission power to maximize hop distance and minimize the number of hops.

B. Criterion for selecting number of hop and hop distance

We use R to denote the distance from source to destination. We use R_{smax} to denote the maximum single-hop distance. Clearly, for the case $R > R_{s\max}$, a single-hop scheme is not feasible. However, we propose to determine the optimal number of communication hops and the optimal distance of each hop in order to minimize the total WSN energy consumption on the path from source to destination.

From the above criteria, we can deduce that the minimum number of hops is the ceiling of $R/R_{s\max}$, denoted as N_h. Furthermore, we can express the distance from source to destination as $R = (N_h - 1) \times R_{s\max} + l, l \le R_{s\max}$. Initially, we consider two possible configurations of the distance between hops: (i) The distance of first $(N_h\text{-}1)$ hops is R_{smax}, and the distance of N_hth hop is l. (ii) The distance of the N_h hops is equal. In the following analysis we will prove that the second scheme is more energy efficient than the first scheme under the assumption that efficiency of the power amplifier, η, is constant.

We denote the total power consumption to transmit data from source to destination with the first scheme and second scheme as P_{t_max} and P_{t_eq} respectively. For simplicity, we assume the path loss exponent is constant, α=2. Then,

$$P_{t\_\max} = (N_h - 1)P_{R0} + N_h P_{T0} + (N_h - 1) \times \frac{\varepsilon \times R_{s\max}^2}{\eta} + \frac{\varepsilon \times l^2}{\eta}$$

$$P_{t\_eq} = (N_h - 1)P_{R0} + N_h P_{T0} + N_h \times \frac{\varepsilon \times (R/N_h)^2}{\eta}$$

$$P_{t\_\max} - P_{t\_eq}$$
$$= (N_h - 1) \times \frac{\varepsilon \times R_{s\max}^2}{\eta} + \frac{\varepsilon \times l^2}{\eta} - N_h \times \frac{\varepsilon \times (R/N_h)^2}{\eta}$$

Because $R = (N_h - 1)R_{s\max} + l$, then,

$$P_{t\_\max} - P_{t\_eq}$$
$$= (N_h - 1) \times \frac{\varepsilon \times R_{s\max}^2}{\eta} + \frac{\varepsilon \times l^2}{\eta} - \frac{\varepsilon \times ((N_h - 1)R_{s\max} + l)^2}{\eta \times N_h}$$
$$= \frac{\varepsilon}{\eta} \times \frac{N_h - 1}{N_h} \times (R_{s\max} - l)^2$$

From the above, clearly $P_{t\_\max} - P_{t\_eq} \ge 0$ which implies that the equidistant sensor node scheme is more energy efficient. Thus, for a 1-D linear N_h hop WSN, the minimal power consumption will be achieved by setting the distance of each hop to be the same, and equal to $\frac{R}{N_h}$.

IV ANALYSIS OF REAL DEVICE

In this section, we present several examples to better illustrate the above analysis. Because the radio environment may be different depending on the conditions, i.e. different ε and α, we concentrate on P_{equiv}, the maximum power for power efficient single hop transmission rather than absolute maximum single hop distance. We use two kinds of widely used RF modules, CC1000 and CC2420, as examples. From ref. [15] and ref. [16], we can obtain the value of P_{R0}, P_{T0}, and P_{max} directly, and estimate η shown as figure 4.1 and figure 4.2. And then we calculate the P_{equiv} according to equation (3-1). Table-1 shows the results.

Table-1 P_{equiv} of commercial Tx/Rx module in wireless sensor node device

	CC1000 @433MHz	CC1000 @868MHz	CC2420 @2.4GhZ[*1]
P_{R0}	22.2mW	28.8mW	59.1mW
P_{T0}	15.9mW	25.8mW	26.5mW
H	15.7%	6.4%	3.7%
P_{max}	10 mW	5mW	1mW
P_{equiv}	12mW	7mW	6.3mW

[*1] One of reasons P_{R0} and P_{T0} for the CC2420 is larger than for the CC1000 is that CC2420 includes circuitry to process a part of the MAC layer. This includes a digital interface with FIFO, CRC and Encryption, while CC1000 is a physical layer only module.

Additionally, it should be noted that it is possible to have a significantly higher drain efficiency, e.g. in ref. [12], η=35% for class A/B class power amplifier, and in ref. [13], η=92.4% for class E power amplifier. Therefore, the value of P_{equiv} can be even larger than P_{max} if more efficient PAs are used.

From the analysis above we discover that for a practical sensor node device, the P_{equiv} is larger than P_{max} which suggest that using P_{max} as the transmit power in order to send data over the furthest distance possible provides the most energy efficient solution. This result directly contradicts the conclusions drawn by using the typical power consumption models used in the WSN research community [3] [19]. The reasons for this discrepancy are explained as follows.

From the equation (3-1), we know that the P_{equiv} depends on P_{R0} and P_{T0}. From the data in Table-1, we found that the measured P_{R0} and P_{T0} are larger than the conventional power consumption model assumes [3] [19].

In addition, the selection of ε_{amp} in the conventional power consumption model (i.e. $E_T(d) = E_{T0} + \varepsilon_{amp}d^2$) [3] is also different from what we observe in physical hardware. Because the conventional model does not separate the power amplifier from other factors, such as the radio environment, it is difficult to quantify the impact of each hardware component on the total power consumption of the device, which may lead to some misleading results when this model is used to guide design decisions.

The parameter values of a real device verify the criteria for selecting a single-hop scheme and for selecting number of hops proposed in section III. We assume the data rate is B, and B is normalized as one data packet per second, then using (2-5), we can obtain Figure 5.

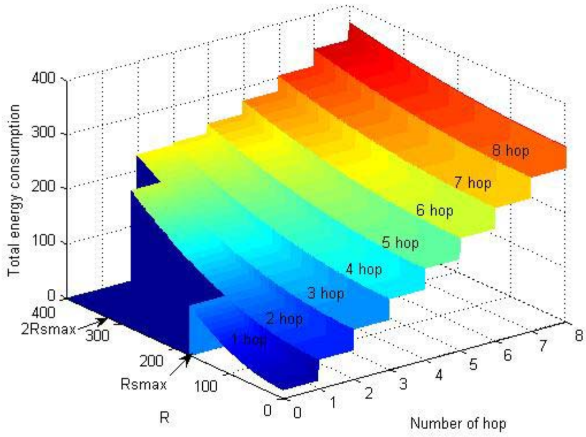


Fig.5 Total energy consumption vs. distance R and number of hops CC1000 @433MHz: P_{R0}=22.2mW, P_{T0}=15.9mW, η=15.7%, α =2, ε=0.0005.Thus, R_{smax} = 155

Fig. 5 shows that when $R \le R_{s\max}$, single hop is most energy efficient; when $R > R_{s\max}$, the most energy efficient number of hops is the upper integer or ceiling of $\frac{R}{R_{s\max}}$.

V ANALYSIS OF OVERHEAD

Besides the energy consumed during the communication of data packets, multi-hop routing schemes result in significant overhead when we consider things like sleeping schedule, and route discovery. We argue that while the goals of these algorithms are the reduction of power consumption and the increase of network lifetime, at same time these supporting algorithms cause overhead. This overhead must be properly analyzed and included in our selection criterion. In this section, we discuss the overhead of multi-hop scheme by analyzing a synchronized sleeping schedule algorithm [8] as an example.

A. Analysis

For our analysis we make the following assumptions:

- multi-hop ($n \ge 2$)
- measured data in one active period of duty cycle is transmitted in one packet
- an algorithm based on [8] is used
- power consumption of the CPU is ignored

Then, in Table-2, we list the main tasks of the algorithm according to a simplified CSMA/CA protocol, where RTS denotes Request-to-Send, CTS denotes Clear-to-Send, and ACK denotes Acknowledgement. For the purposes of our analysis, the time spent waiting for an empty channel is t_1; the time spent listening for an RTS is t_2; the length of all control packets (RTS, CTS, and ACK) is k_1 bits; and all data packets are the same size, k_2 bits.

Table-2 Basic tasks in a synchronized sleeping schedule [8]

Node in transmitting mode	Node in receiving mode	Nodes in idle listening mode
Listening for channel empty (t_1)	Listening for RTS (t_2)	Listening for RTS (t_2)
Transmitting RTS (k_1 bits)	Receiving RTS (k_1 bit)	
Receiving CTS (k_1 bits)	Transmitting CTS (k_1 bits)	
Transmitting data (k_2 bits)	Receiving data (k_2 bits)	
Receiving ACK (k_1 bits)	Transmitting ACK (k_1 bits)	

We use $E_{total\_m}(n)$ to denote the total energy consumption for sending data from source to destination via n-hops; we further define $E_{total\_rx}(n)$, $E_{total\_tx}(n)$ and $E_{total\_idle}(n)$ denote the total energy consumption for receiving, for transmitting, and for idle listening. We use E_{rx_1}, E_{tx_1}, E_{idle_1} denote the energy consumption for a single node according to its mode of operation (receiving, transmitting, or idle listening). Thus,

$$E_{total\_m}(n) = E_{total\_rx}(n) + E_{total\_tx}(n) + E_{total\_idle}(n)$$
$$= (n-1)E_{rx\_1} + nE_{tx\_1} + n(n-2)E_{idle\_1}$$

In other words, in order to send one data packet from source to destination we need n units of transmission mode energy and $n-1$ units of receive mode energy. The operation sequence occupies n duty cycles, in each duty cycle $n-2$ nodes are in idle listening mode. Thus the entire network consumes $n \times (n-2)$ units of idle listening mode energy. Using the characteristics described in Table-2, we express E_{rx_1}, E_{tx_1}, E_{idle_1} using the following: the energy consumption for idle listening in a unit time (E_{idle}), the energy consumption for receiving one bit (denoted as E_R), and the energy consumption for transmitting one bit over the distance R/n (denoted as $E_T(n)$), Then,

$$\begin{aligned} & E_{total\_m}(n) \\ & = (n-1)(E_{idle} \times t_2 + E_R \times (k_1 + k_2) + E_T(n) \times (k_1 + k_1)) \quad (5\text{-}1) \\ & + n(E_{idle} \times t_1 + E_R \times (k_1 + k_1) + E_T(n) \times (k_1 + k_2)) \\ & + n(n-2)(E_{idle} \times t_2) \end{aligned}$$

For a single hop network, a sleeping schedule is not required and we only need to consider the power consumption of the source node, while assuming destination node is not resource constrained. Consequently, the source node performs the following tasks: listening for an empty channel over the interval t_1, transmitting k_2 bits of a data packet, and receiving k_1 bits of an ACK packet. We use E_{total_s} denote the total energy consumption for sending a data packet from source to destination via a single hop, $E_T(1)$ denote the power consumption for transmitting one bit from source to destination directly. Then,

$$E_{total\_s} = E_R \times k_1 + E_T(1) \times k_2 + E_{idle} \times t_1 \qquad (5\text{-}2)$$

Similarly, it can be shown that there is one and only one minimum point on the curve of $E_{total\_m}(n)$, where $n > 0$, $\alpha > 1$. When comparing the function of E_{total_s} and $E_{total\_m}(n)$ above, it is clear that $E_{total\_s} < E_{total\_m}(1)$. Therefore, it is can be deduced that if $E_{total\_s} < E_{total\_m}(2)$ then $E_{total\_s} < E_{total\_m}(k)$, where $k > 2$. As a consequence, we can simplify the analysis and only compare a single-hop network with a 2-hop network. That means that we need to find the optimal transmit power level and the range of R which satisfies $E_{total\_s} \le E_{total\_m}(2)$. Using the definition of E_{total_s} and $E_{total\_m}(n)$, Then,

$$\begin{aligned} &E_{total\_m}(2) - E_{total\_s} \\ &= E_{idle} \times (t_2 + t_1) + E_R \times (4k_1 + k_2) + E_T(2) \times (4k_1 + 2k_2) - E_T(1) \times k_2 \end{aligned}$$

To further refine the analysis we use the time interval defined by the 802.15.4 standard as a basic time unit. Then, the interval for waiting channel empty is relatively short; the time waiting for RTS is equal to one time unit; and time to transmit a single the control packet can also be defined as one time unit. Thus, we can assume t_1=0, t_2 equal to the interval for transmitting k_1 bits data. In typical transceiver hardware we find $P_{idle} = P_R$. Thus, $E_{idle} \times t_2 = E_R \times k_1$. Then,

$$\begin{aligned} &E_{total\_m}(2) - E_{total\_s} \\ &= E_R \times (5k_1 + k_2) + E_T(2) \times (4k_1 + 2k_2) - E_T(1) \times k_2 \end{aligned}$$

We assume the data rate is constant, denoted as B. We replace the equation above with B and equation (2-3) and (2-5), and set it to be less than or equal to zero to satisfy $E_{total\_s} \le E_{total\_m}(2)$. Then we obtain the following equations.

$$P_{Tx}(R_s) \le \min\left(\frac{((5k_1 + k_2) \times P_{R0} + (4k_1 + k_2) \times P_{T0}) \times \eta}{((1 - 2^{1-\alpha})k_2 - 2^{2-\alpha} k_1)}, P_{\max} \right) \quad (5\text{-}3)$$

$$R_s \le \min\left(\sqrt[\alpha]{\frac{((5k_1 + k_2) \times P_{R0} + (4k_1 + k_2) \times P_{T0}) \times \eta}{((1 - 2^{1-\alpha})k_2 - 2^{2-\alpha} k_1) \times \varepsilon}}, \sqrt[\alpha]{\frac{P_{\max}}{\varepsilon}} \right) \quad (5\text{-}4)$$

B. Example

In the following analysis we use the IEEE 802.15.4 standard [17] as an example to illustrate the impact of overhead on the total power consumption of the network. For our analysis we use the data frame (Figure 6) and the algorithm described in Table-2.

Assume the address field is 4 bytes, the payload for RTS, CTS, and ACK is 4 bytes, which is similar to the average implementation of 802.11 [18]. The payload for data has the maximum length, which is 127 – (2+1+8+2) = 114 Bytes. Then, k_1=19 bytes, and k_2 =133 bytes.

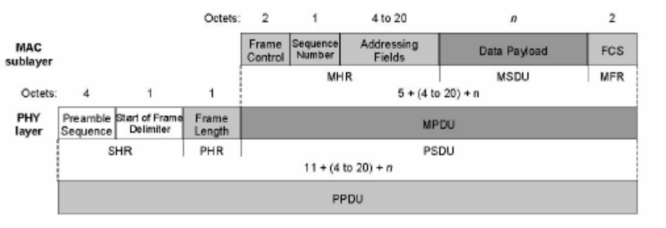


Fig. 6 Schematic view of the data frame

Assume α =2. Then,

$$P_{Tx}(R_s) \le 2\eta \times \left((1 + \frac{7k_1}{k_2 - 2k_1}) \times P_{R0} + (1 + \frac{6k_1}{k_2 - 2k_1}) \times P_{T0} \right)$$

Assume P_{R0}=P_{T0}. The overhead of the sleeping schedule will cause P_{equiv} to increase by $\frac{13k_1}{k_2 - 2k_1}$.Using the assumption of k_1 and k_2 above, we found that the range of P_{equiv} , to which single hop is more energy efficient than multi-hop, will increase about 160%, and the maximum R_s will increase 61%.

The analysis concludes that the range of P_{equiv}, and R_s, over which a single-hop network is more energy efficient, becomes larger if we include the overhead required by multi-hop routing into consideration.

We analyze the impact of overhead on the total energy consumption when sending data from source to destination via single-hop or multi-hop. Assume we transmit data with P_{equiv}, defined in (3-1), that means the distance of one hop is R_{smax}. Then, with equation (2-5) and equation (5-1) (5-2), we define energy efficiency of communication for the n-hop scheme (denoted as γ(n)) as follows:

$$\gamma(1) = \frac{(P(1)/B) \times k_2}{E_{total\_s}} = \frac{(P_{T0} + \frac{\varepsilon \times R^\alpha}{\eta}) \times k_2}{P_{R0} \times 2k_1 + (P_{T0} + \frac{\varepsilon \times R^\alpha}{\eta}) \times k_2} \qquad n=1$$

$$\begin{aligned} \gamma(n) &= \frac{(P(n)/B) \times k_2}{E_{total\_m}(n)} \\ &= \frac{P_{R0}(n-1)k_2 + (P_{T0} + \frac{\varepsilon \times (R/n)^\alpha}{\eta}) \times nk_2}{P_{R0}((n^2 + 2n - 2)k_1 + (n-1)k_2) + (P_{T0} + \frac{\varepsilon \times (R/n)^\alpha}{\eta})(3nk_1 - 2k_2 + nk_2)} \qquad n>1 \end{aligned}$$

If we compare the above results with the analysis in Section IV, the total energy consumption with overhead for sending a data packet from source to destination via n-hop, at normalized data rate B defined in section IV, denoted as $P_{ov}(n)$, is $P_{ov}(n) = \frac{P(n)}{\gamma(n)}$. From Figure 7 we conclude if the overhead required by a multi-hop network is considered, networks with a large number of hops will be less desirable from an energy consumption perspective.

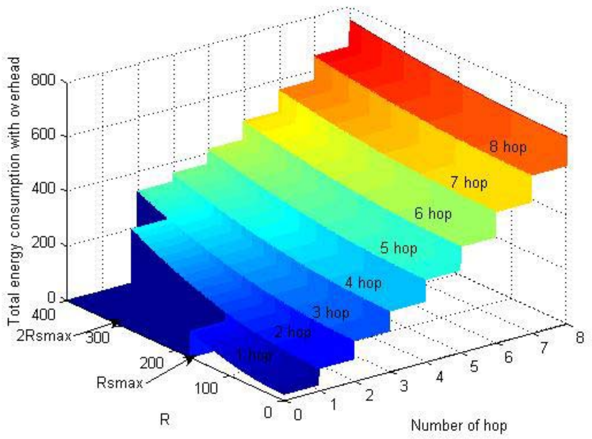


Fig.7 Total energy consumption with overhead vs. distance R and number of hop. CC1000 @433MHz: P_{R0}=22.2mW, P_{T0}=15.9mW, η=15.7%, α =2, ε=0.0005.Thus, $R_{smax} = 155$

In the analysis above, we only consider the energy consumed by the communication module, and ignore the power consumption for the other parts, such as the microprocessor and memory. In fact, the energy consumed by the other parts is comparable with the energy consumed by the RF module [7]. Multi-hop routing requires each node wake up periodically, which not only consumes the power while idle listening, and transmitting/receiving the overhead bits, but also consumes power for processing the protocol in the microprocessor. Thereby, if we take the power consumption of processing into account, the power consumption of a multi-hop network will increase and a single hop network will look even more desirable.

VI POTENTIAL APPLICATIONS

In this section, we apply our criterion for selecting the optimal number of hops described in Section III with some potential application scenarios. These scenarios include: topology design and placement of nodes in heterogeneous networks, energy efficient routing, power management, and guidelines for future hardware designs.

A. Placement of Nodes in a Heterogeneous Network

The network consists of three kinds of nodes, one sensor node, *n-1* relay nodes, and one sink. The sensor node collects data and transmits data to sink directly or via relay nodes. Relay nodes forward data. The sink receives data from sensor nodes or relay nodes. The relay nodes can be placed at any location as needed. We use equations (3-1) and (3-2) to determine the number of relay nodes and where the optimal location of relay nodes is, in terms of energy efficiency.

We assume R_{smax} is a reachable distance under P_{equiv} defined in section III and calculated with equation (3-1). Assume the distance between the sensor node (denoted as N_0) and sink is *R*. If $R \le R_{s\max}$, then the node N_0 uses proper transmit power to transmit data to sink directly. If $R > R_{smax}$, and then assume that *R* is some multiple times of R_{smax}, $n = \lceil R / R_{s\max} \rceil$, then we can insert *n-1* relay nodes between the N_0 and the sink equidistantly, denoted as N_i, *i=1..n-1*. Each node N_i, *i=0..n-1* uses P_{equiv} to transmit data to N_{i+1} or sink.

B Best Effort Routing Algorithm in Homogeneous network (BERA)

The network consists of two kinds of nodes, some sensor nodes and one sink. Each sensor node collects data, transmits data, or forwards data. The sink receives data from sensor nodes. Similarly, all of the nodes are deployed on a line equidistantly. We use equations (3-1) and (3-2) to determine the optimal next hop node in terms of path energy efficiency.

Assume there are *m* sensor nodes, denoted as N_i, *i=0..m-1*, the distance between node N_i and N_{i+k} is R_{smax}. Then N_i, *i=0..m-k-1*, should use the P_{equiv} to transmit or forward data to N_{i+k}, and N_j, *j=m-k..m-1* use relatively lower power to transmit or forward data to sink. From the analysis in section III, we can conclude that, with BERA, the closest possible energy efficient path can be obtained. Comparing with the second scheme defined in section III.B, the power consumption of BERA may be higher. But BERA is simple to implement, because it does not require any initial information about the distance from the source to destination.

For a 2-dimension network, we can also use BERA by adding a constraint to direction of transmission, which guarantees that the data is forwarded toward to sink. And for the 2-dimension network with obstacles, we can use the radio distance, which is determined by the receive signal strength, to replace the distance mentioned above, and then BERA algorithm still works.

C. Guidelines for Hardware Design

We can also use our hop selection criterion to evaluate design trade-offs for future hardware devices. Here we evaluate the power plan of the communication module as an example.

From equation in section III we know that

$$P_{Tx}(R_s) \le \min\left(\frac{(P_{R0} + P_{T0}) \times \eta}{(1 - 2^{1-\alpha})}, P_{\max} \right)$$

Divide it by P_{max}, then,

$$\frac{P_{Tx}(R_s)}{P_{\max}} \le \min\left(\frac{(P_{R0} + P_{T0}) \times \eta}{(1 - 2^{\alpha}) \times P_{\max}}, 1 \right)$$

t P_{dc_max} denote the total power consumption of the PA for the maximum output power P_{max}, then,

$$\frac{P_{Tx}(R_s)}{P_{\max}} \le \min\left(\frac{(P_{R0} + P_{T0})}{(1 - 2^{\alpha}) \times P_{dc\_\max}}, 1 \right)$$

In order to make the maximum transmission power of device (i.e. P_{max}) useful, the following equation must be satisfied.

$$\frac{(P_{R0}+P_{T0})}{(1-2^{\alpha})\times P_{dc\_\max}} \geq 1$$

Assume α=2, Then,

$$2\times(P_{R0}+P_{T0}) \geq P_{dc\_\max}$$

From the equation above, we derive design guidelines for the communication module: the maximum power consumption of the PA should not be greater than twice the total power consumption of the other hardware components in the communication module. In another words, if P_{dc_max} is greater than two times the total power consumption in the other part of circuit, then P_{max} will never be used because a network of shorter multi-hops will more energy efficient than transmitting at P_{max} in this scenario.

VII RELATED WORK

Recently, there have been a few comparative studies of single hop vs. multi-hop networks published. References [1] [4] suggest reasons for not routing over many short hops. Ref. [2] compares single hop scheme with multi-hop scheme in term of interference, and concludes that single-hop routing outperforms two-hop routing for bandwidth-normalized rates larger than the path-loss exponent. In [5] the authors studied the impact of power amplifier characteristics on routing in a wireless network. It used the following power amplifier model $P_{dc} = \beta P_{Tx} + P^*$, $0 \leq P_{Tx} \leq P_{\max}$, where P_{dc} is the total power consumption of power amplifier, P_{Tx} is output power, P_{max} is the maximum output power, P^* is the total static power consumption, β is slope, which ranges from 0 to 2. From the definition of generic amplifier, $\beta=1$and $P^*= P_{max}$, ref. [5] concludes that for a generic amplifier, there is no energy benefit in using multiple hops, if the destination can be reached at maximum radio power directly. In addition some researchers recognized the advantages of a single-hop scheme and developed coding techniques, which improve the valid range of single hop networks [11].

One research group has proposed the following model for the power consumption of a communication module [3].

$$E_T(d) = E_{T\text{-}elec} + \varepsilon_{amp} d^2$$

$$E_R = E_{R\text{-}elec}$$

Where, the path loss exponent is assumed 2; the parameters $E_{T\text{-}elec}$ and $E_{R\text{-}elec}$ are the per-bit power consumptions for transmission and reception, respectively. The unit for $E_{T\text{-}elec}$ and $E_{R\text{-}elec}$ is nJ/bit, and unit for ε_{amp} is pJ/bit/m^2. It is assumed that $E_{T\text{-}elec} = E_{R\text{-}elec} = E_{elec}$ = 50nJ/bit, and ε_{amp}= 100pJ/bit/m^2. Other researchers extended the power consumption model where the path loss exponent includes 2 and 4 [19].

$$E_T(d) = \begin{cases} E_{T\_elec} + \varepsilon_{fs} \times d^2, d < d_0 \\ E_{T\_elec} + \varepsilon_{mp} \times d^4, d \geq d_0 \end{cases}$$

$$E_R = E_{R\text{-}elec}$$

Where, $E_{T\text{-}elec} = E_{R\text{-}elec} = E_{elec}$ = 50nJ/bit, and ε_{fs}= 10pJ/bit/m^2, and ε_{mp}= 0.0013pJ/bit/m^4.

Ref. [9] takes the characteristics of power amplifier into account separately, but does not analyze the impact of the parameters on the transmission power and distance of communication.

Based on the power consumption model defined in [3] [19], ref. [10] deduced the upper limit of energy efficient single hop distance as follows. If $d \geq \left(\frac{E_{T\_elec}+E_{R\_elec}}{(1-2^{1-\alpha})\times\varepsilon_{amp}}\right)^{1/\alpha}$, where d is the distance between source S and destination D, then there exists an intermediate node between S and D so that the retransmission will save energy.

In the literature that evaluates the energy efficiency of a wireless sensor network, almost all use the power consumption model mentioned in [3] [19]. For example, [20] uses the model to study energy efficient routing protocol; [21] uses the model to derive a cross design including PHY, data link, and network layer; [22] uses the model study the placement of relay nodes in heterogeneous wireless sensor network.

VIII CONCLUSION

In this work we extract the impact of communication hardware on total power consumption. We found that the components of power consumption that are a function of distance not only depend on the parameters of the radio environment (i.e. ε and α), but also depends on the drain efficiency of the power amplifier (i.e. η). We propose a power consumption models for a WSN device, and for a multi-hop network, which include such parameters as ε, α and η. This power consumption model provides a clear break down of the major components, which consume power in a WSN. The current model used by the sensor network community does not provide this level of insight, but instead mixes the sources of power consumption together.

Based on the power consumption model, we deduce the upper limit of energy efficient transmission. We show that, in a given radio environment, the upper limit of energy efficient transmission power is proportional to the power consumption of Tx/Rx circuits (parameterized by P_{R0} and P_{T0}), and also proportional to the drain efficiency of power amplifier (Parameterized by η). Based on the upper limit, we deduce the necessary condition for energy efficient data transmission in wireless sensor networks. We show for optimal energy efficiency, it is necessary to choose the P_{equiv}, as the transmit power as often as possible. We also derive an energy efficiency criterion for selecting the optimal number of hops. We show that a single hop scheme should be selected when the destination is reachable with $P_{Tx}(R_s)$, where $P_{Tx}(R_s) \le \min\left(\frac{(P_{R0}+P_{T0})\times\eta}{(1-2^{1-\alpha})}, P_{\max}\right)$. In another words, the multi-hop scheme is more energy efficient than the single hop scheme only when the distance from source to destination is longer than what can be reached with the single hop transmitting power. We also present the criterion for selecting the number of hop and hop distance when multi-hop scheme has to be used. In addition, we show that the P_{equiv}, is usually larger than the maximum transmitting power of current sensor node devices, i.e. P_{max}, that means using P_{max} as transmitting power is the most energy efficient solution for most practical scenarios.

By taking the overhead of a sleeping schedule as an example, we show that the upper limit of energy efficient transmitting power and single hop distance rises dramatically when the overhead required by multi-hop is taken into account. For example, the transmitting power increases about 160% with the conditions described in section V, and the optimal distance of single hop rises about 61%. In addition, we want to emphasize that the analysis here is very conservative because not all of the overhead of multi-hop is included, such as the overhead for time synchronization, and the overhead for route discovery.

We argue that the results of this work can be used to guide many layers of the design space and provide several application examples. In the future we plan on using the analysis described here to guide design choices in future WSN implementations. Some areas of investigation include: topology design, power management algorithms, energy efficient routing protocols, and sensor node device architecture.

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