An Analytical Energy Consumption Model for Packet Transfer over Wireless Links

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***Abstract*—We provide a detailed analytical model for estimating the total energy consumed to exchange a packet over a wireless link. Our model improves many of the current models by considering details such as consumed energy by processing elements of transceivers, packet retransmission, reliability of links, size of data packets and acknowledgments, and also the data rate of wireless links. To develop the model, we use experimental results based on IEEE 802.15.4 devices to show that consumed energy for receiving erroneous packets is comparable to the consumed energy for receiving error-free packets.**

***Index Terms*—**

I. INTRODUCTION

DATA communication with high energy efficiency is an important requirement in wireless networks. To address this we need accurate models of energy consumption. Without the use of such models any designed mechanism may not be optimal and any analysis may result in poor approximation.

In this letter, we develop a mathematical model for energy consumption of nodes for packet exchange over wireless links. Inclusion of details such as consumed energy by processing elements of transceivers, reliability of wireless links, packet retransmissions at the MAC (medium access control) layer, size of data and acknowledgment packets, and data rate of wireless links makes our model very detailed compared to the other models [1]–[3].

Studies such as [1], [2], only model consumed energy during a single transmission and reception of a packet. They do not take into account the effect of packet retransmission at the MAC layer on energy consumed for packet exchange. By taking into account the effect of packet retransmission, our model brings into picture the effect of reliability of wireless links on the energy consumption of nodes. Our model also enhances the proposed model in [3] by limiting the number of times that a lost packet is allowed to be retransmitted. It is assumed in [3] that there is no limitation on the number of transmission attempts. Furthermore, [3] assumes, without any verification, that the same amount of energy is consumed for receiving lost and error-free packets. We used 2.4 GHz IEEE 802.15.4 devices to verify this assumption by showing that *a high percentage* of lost packets over a wireless link are discarded after being completely detected by the receiver. These packets are discarded due to CRC (cyclic redundancy check) failure, which is performed on detected and reconstructed packets at the receiver. This implies that the consumed energy for receiving lost packets is comparable with the consumed energy for receiving packets successfully.

The rest of this letter is structured as follows: We present the energy consumption model in Section II. In Section III, we determine the expected number of transmission attempts of a data packet and its acknowledgment. We present experimental and simulation results in Section IV. We conclude in Section V.

II. ENERGY CONSUMPTION MODEL FOR PACKET EXCHANGE OVER WIRELESS LINKS

Consumed energy by nodes during packet transmission could be abstracted into two distinct parts [1], [2]. The first part represents the energy consumed by the processing circuit of the transmitter (baseband processing). The second part represents the energy consumed by the power amplifier of the transmitter to generate the required output power for data transmission over the air. On the other hand, the energy consumed by a node to receive a packet could be abstracted by only one part, which is the energy consumed by the receiving circuit including the low noise amplifier (LNA) of the receiver.

Let (u, v) denotes the wireless link between sender u and receiver v. Let r be the rate at which u transmits data to v over the physical link (u, v), P_t be the power required to run the processing circuit of the transmitter, P_r be the power required to run the receiving circuit, $P_{u,v}$ be the transmission power from u to v, and κ be the efficiency of the power amplifier. The energy consumed by u to transmit a packet of length x bits over (u, v) is

$$\varepsilon_{u,v}(x, r) = \left(P_t + \frac{P_{u,v}}{\kappa}\right) T = \left(P_t + \frac{P_{u,v}}{\kappa}\right) \frac{x}{r} \qquad (1)$$

in which T is the time required to transmit x bits with the rate r bps. The energy consumed by v to receive the packet from u is

$$\omega_{u,v}(x, r) = \frac{P_r}{r} x. \qquad (2)$$

The transmission power $P_{u,v}$ could be the maximum transmission power of nodes P_{max}. Alternatively, it could be the power adjusted due to transmission power control scheme [4].

In accordance with wireless technologies IEEE 802.11 and IEEE 802.15.4, we assume that the receiver transmits an acknowledgment to the sender for each correctly received packet. If the sender does not receive an acknowledgment, it will retransmit the packet. This may happen because either the packet or its acknowledgment is lost. The sender retransmits the packet until it receives an acknowledgment, or the maximum number of transmission attempts M is reached. Therefore, a packet or its acknowledgment might be

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Manuscript received April 3, 2011. The associate editor coordinating the review of this letter and approving it for publication was S. Gupta.

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Digital Object Identifier 10.1109/LCOMM.2011.101011.110729

transmitted $m \leq M$ times. This means, the actual energy consumed to exchange a packet over a wireless link must include the energy consumed during retransmissions as well.

Let $\mathcal{X} \in \{1, 2, ..., M\}$ be the number of times that a packet is transmitted, including the first transmission, and $\mathcal{Y} \in \{0, 1, 2, ..., M\}$ be the number of acknowledgments transmitted for the packet. For the time being let us assume that the energy consumed by the receiver for receiving and decoding a corrupted packet is the same as the energy consumed for receiving an error-free packet. In Section IV, we shall verify this assumption. Let L_d (bits) denote the size of the data packet transmitted from u to v, L_a (bits) denote the size of the acknowledgment, R_d denote the data rate with which the data packet is transmitted by u, and R_a denote the data rate by which the acknowledgment is transmitted by v. The total consumed energy by u to deliver the packet to v is

$$e_t(u, v) = \mathcal{X}\varepsilon_{u,v}(L_d, R_d) + \mathcal{Y}\omega_{v,u}(L_a, R_a) \tag{3}$$

Similarly, the total energy consumed by v to receive the packet is

$$\begin{aligned} e_r(u, v) &= \mathcal{X}\omega_{u,v}(L_d, R_d) + \mathcal{Y}\varepsilon_{v,u}(L_a, R_a) \\ &= \mathcal{X}\frac{P_r L_d}{R_d} + \mathcal{Y}\left(P_t + \frac{P_{v,u}}{\kappa}\right)\frac{L_a}{R_a}. \end{aligned} \tag{4}$$

The value of $\mathcal{X}$ and $\mathcal{Y}$ depends on reliability of the forward link (u, v) for data packets and reliability of the reverse link (v, u) for acknowledgments. Thus, the total consumed energy by nodes to exchange a packet over a wireless link depends on reliability of the links as well. It may even happen that the receiver consumes more energy compared to the sender. This of course depends on various parameters in (3) and (4).

In the next section, we determine the probability density function (PDF) of $\mathcal{X}$ and $\mathcal{Y}$. This allows us to determine the expected number of times that a data packet is transmitted $E[\mathcal{X}]$ as well as the expected number of times that an acknowledgment is transmitted for the data packet $E[\mathcal{Y}]$. They are needed to calculate the expected amount of energy consumed by the sender and the receiver to exchange a data packet, which are as follows:

$$\begin{cases} E[e_t(u,v)] = E[\mathcal{X}]\left(P_t + \frac{P_{u,v}}{\kappa}\right)\frac{L_d}{R_d} + E[\mathcal{Y}]\frac{P_r L_a}{R_a} \\ E[e_r(u,v)] = E[\mathcal{X}]\frac{P_r L_d}{R_d} + E[\mathcal{Y}]\left(P_t + \frac{P_{v,u}}{\kappa}\right)\frac{L_a}{R_a}. \end{cases} \tag{5}$$

III. EXPECTED NUMBER OF TRANSMISSION ATTEMPTS OF DATA AND ACKNOWLEDGMENT PACKETS

A packet will be transmitted m times if the packet itself or its acknowledgments is lost in the last $m - 1$ transmission attempts. Therefore,

$$\Pr\{\mathcal{X} = m\} = \begin{cases} (1 - pq)^{m-1}pq, \ m = 1, ..., M - 1, \\ (1 - pq)^{M-1}, \ m = M, \end{cases} \tag{6}$$

where p is the delivery probability of a data packet of size L_d bits transmitted over (u, v), and q is the delivery probability of an acknowledgment of size L_a bits transmitted over (v, u). From (6), we have

$$\begin{aligned} E[\mathcal{X}] &= M(1 - pq)^{M-1} + \sum_{m=1}^{M-1} mpq(1 - pq)^{m-1} \\ &= \frac{1 - (1 - pq)^M}{pq}. \end{aligned} \tag{7}$$

To derive (7), we used the identity $\sum_{m=1}^{n} z^m = z\frac{1-z^n}{(1-z)^2} - \frac{nz^{n+1}}{1-z}$ considering $z = 1 - pq$ and $n = M - 1$. Note that for sufficiently large M, $(1 - pq)^M \to 0$. Thus, we can write that $E[\mathcal{X}] \to \frac{1}{pq}$. This means, for any limited value of M, we have $E[\mathcal{X}] \leq \frac{1}{pq}$.

Next, we determine $\Pr\{\mathcal{Y} = m\}$, $\forall m \in \{0, 1, ..., M\}$. If a data packet is lost during all possible transmission attempts, no acknowledgment will be transmitted for it. Hence, $\Pr\{\mathcal{Y} = 0\} = (1 - p)^M$. On the other hand, an acknowledgment will be transmitted M times for a data packet, if the data packet is received correctly in every transmission attempt, but all $M - 1$ acknowledgments transmitted for it are lost. Thus, $\Pr\{\mathcal{Y} = M\} = p^M(1 - q)^{M-1}$.

Let us calculate the probability of transmitting $0 < m < M$ acknowledgments for a data packet. An acknowledgment is transmitted only when the data packet is correctly received. Of course, a packet might be received correctly after a number of transmission attempts. If the transmitted acknowledgment for the packet is lost, the sender will retransmit the packet. Hence, another acknowledgment will be transmitted, if the data packet is again received correctly after a number of attempts. We should also notice that the maximum number of transmission attempts of a data packet is limited, which adds to the complexity of the analysis.

To determine $\Pr\{\mathcal{Y} = m$, $0 < m < M$, we consider two possible cases. In the first case, the M^{th} transmission of the data packet never happens, because the sender receives an acknowledgment for the packet before reaching the maximum transmission attempts M. In such a case, $m - 1$ out of the first $n - 1$, $\forall n \in \{m, m + 1, m + \cancel{1}, ..., M - 1\}$, transmission attempts of the data packet could be successful, but all $m - 1$ acknowledgments transmitted for it should be lost. The m^{th} transmission of the data packet must be successful, and its acknowledgment must also be received successfully. The probability of this event is~~.~~

$$E_1 = \sum_{n=m}^{M-1} \binom{n-1}{m-1} p^{m-1}(1 - q)^{m-1}(1 - p)^{n-1-(m-1)}pq$$

In the second case, the sender transmits the data packet M times, because it has not received an acknowledgment after $M - 1$ attempts. Here, we face two subcases. In the first subcase, $m - 1$ out of the first $M - 1$ transmission attempts of the packet are successful, but all its $m - 1$ acknowledgments are lost. The M^{th} transmission attempt of the packet is also successful, which triggers transmission of the m^{th} acknowledgment. The probability of this event is~~.~~

$$E_2 = \binom{M-1}{m-1} p^{m-1}(1 - p)^{M-1-(m-1)}(1 - q)^{m-1}p$$

In the second subcase, m out of the first $M - 1$ transmission attempts of the packet are successful, but all m acknowledgments transmitted for it are lost. The M^{th} transmission attempt of the packet fails, which prevents transmission of another acknowledgment. The probability of this event is.

$$E_3 = \binom{M-1}{m} p^m (1-p)^{M-1-m} (1-q)^m (1-p)$$

The probability of transmitting $1 \leq m \leq M-1$ acknowledgments for the packet is then $E_1 + E_2 + E_3$. In summary,

$$\Pr\{\mathcal{Y} = m\} = \begin{cases} (1-p)^M, \ m = 0; \\ E_1 + E_2 + E_3 \quad m = 1..M-1; \\ p^M (1-q)^{M-1}, \ m = M. \end{cases} \tag{8}$$

Given p and q, we can compute $E[\mathcal{Y}]$ for any value of M using its PDF given by (8). Unfortunately, no closed-form expression could be found for $E[\mathcal{Y}]$ when M is finite. However, if there is no limitation on the number of transmission attempts of a packet, $M \to \infty$, we can find a closed-form expression. In such a case, a packet can be retransmitted as many times as required until the receiver receives the packet successfully. Therefore, the expected number of times that an acknowledgment is transmitted for a packet is simply $E[\mathcal{Y}] = \frac{1}{q}$. As a result, for any limited value of M we have $E[\mathcal{Y}] \leq \frac{1}{q}$.

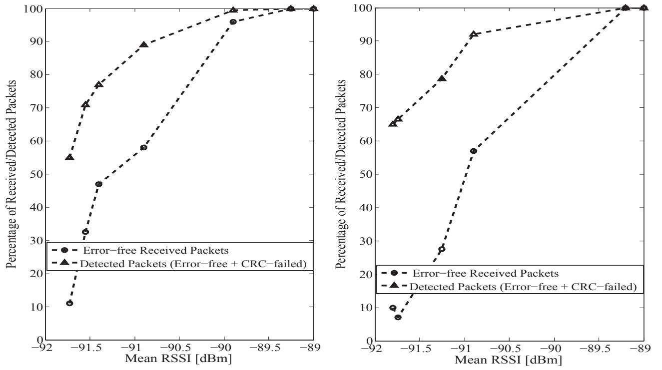
Using (5) and considering the two inequalities, $E[\mathcal{X}] \leq \frac{1}{pq}$ and $E[\mathcal{Y}] \leq \frac{1}{q}$, the expected energy consumed by sender and a receiver to exchange a packet over the wireless link is upper-bounded as

$$\begin{cases} E[e_t(u,v)] \leq \left(P_t + \frac{P_{u,v}}{\kappa}\right) \frac{L_d}{pqR_d} + \frac{P_r L_a}{qR_a} \\ E[e_r(u,v)] \leq \frac{P_r L_d}{pqR_d} + \left(P_t + \frac{P_{v,u}}{\kappa}\right) \frac{L_a}{qR_a} \end{cases} \tag{9}$$

where the equality happens if M is unlimited.

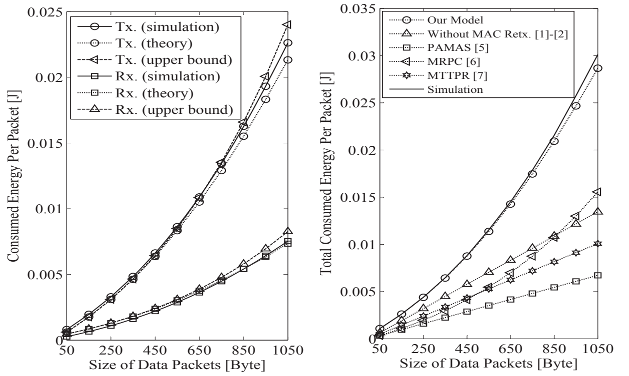
IV. EXPERIMENTAL AND SIMULATION RESULTS

According to IEEE 802.11 and IEEE 802.15.4 standards, there are several possibilities in which a packet could be lost. The packet may not be detected by the physical layer (PHY) at all due to low received signal to noise ratio or due to corrupted preamble. Even if a packet is detected completely, it may contain erroneous bits. Some errors might be corrected by FEC (Forward Error Correction) techniques. Nevertheless, some bits may still remain erroneous after FEC. Then, CRC is performed to ensure the reception of error-free packets to higher layers. If a packet fails to pass CRC, it will be discarded (lost). We used T-mote devices based on the CC2420 chipset (IEEE 802.15.4) to show that a high percentage of packets lost over a wireless link are CRC-failed packets. Note that CRC is performed on packets which have been detected completely (like error-free packets). Hence, we may conclude that most of the time nodes consume the same amount of energy to detect a lost packet as that of receiving the packet correctly. To verify this, we modified T-mote devices to report CRC-failed packets too. Only packets which have not been detected at all were not reported to higher layers. The receiver was placed at different distances from the sender to have different signal strengths. At each location, 100000 packets were transmitted by the sender. The receiver counted both error-free received packets and CRC-failed packets. As Fig. 1 shows, even if only 10% of the packets are received error-free, around 55% (65%) of them have been detected (correct reception or erroneous) for 10Byte (100Byte) packet sizes. That is, when practically there is no link between the two nodes due to high packet drop rate, many of the transmitted packets have been detected completely. When quality of the link improves, the percentage of detected packets gets closer to 100%. For instance, in Fig. 1(b), when 65% of transmitted packets are received error free, 92% of them have been detected. Only 8% have not been detected at all. Thus, if there is a link between two nodes with an acceptable quality, the consumed energy for reception of lost packets is almost equal (on an average) to the consumed energy for reception of error-free packets.



(a) Packet size = 10 Byte (b) Packet size = 100 Byte

Fig. 1. Percentage of received and detected packets as a function of the mean received signal strength indicator (RSSI).



(a) Our model (b) Comparison with other models

Fig. 2. Total energy consumed by a sender and a receiver to exchange a packet over a physical link. We assumed $\delta = 1 \times 10^{-4}$, $P_t = P_r = 100\text{mW}$, $P_{u,v} = 200\text{mW}$, $\kappa = 1$, $R_d = R_a = 250\text{kb/s}$, $M = 4$, $L_a = 30\text{B}$. Size of the preamble is one octet.

We also present simulation results to verify the accuracy of our energy consumption model. In our simulatons, 100000 data packets are transmitted over a physical link between a sender and a receiver to measure the average amount of energy consumed to exchange a packet. $\varepsilon_{u,v}(x,r)$ and $\omega_{u,v}(x,r)$ are consumed for each transmitted and received packet, respectively. Nevertheless, if an erroneous bit is detected at the preamble of a packet, no energy is consumed for reception of that packet[1]. We also compute theoretical values and their upper bounds using (5) and (9), respectively. To this end, we compute the delivery probability of a packet of size $l \in \{L_d, L_a\}$ bits as $(1-\delta)^l$, where δ is the bit error rate of the link. As Fig. 2(a) shows, the analytical model can accurately

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[1] We assume bit errors in a packet occur independently from each other.

predict the total energy consumed to exchange a packet over a link. The upper bound tends to be very tight when packet size decreases. Moreover, we observe in Fig. 2(b) that neglecting the impact of MAC retransmissions and energy consumption of processing elements of transceivers by existing models can result in substantial inaccuracy in estimating the total energy required for packet exchange over wireless links. In Fig. 2(b), PAMAS, used in [5], refers to a model which neglects the impact of MAC retransmissions as well as energy consumption by processing elements of transceivers. BAMER, used in [6], refers to a model which considers the impact of MAC retransmissions but neglects energy consumption by processing elements of transceivers. MTTPR, used in [7], is similar to PAMAS with the difference that MTTPR considers the energy consumed by processing elements of the receiver. We observe that existing models are not very accurate compared to our model especially when the packet length is higher.

V. CONCLUSION

We provided an analytical model for energy consumed to exchange a packet over a wireless link. The accuracy of the model was verified using experimental and simulation results. We used T-mote devices (IEEE 802.15.4) to show that the consumed energy for receiving lost and error-free packets are comparable, since a high percentage of lost packets are discarded due to CRC failure. The next step is to use this accurate energy consumption model to design energy-efficient protocols for wireless multi-hop networks.

REFERENCES

[1] Q. Wang, M. Hempstead, and W. Yang, “A realistic power consumption model for wireless sensor network devices,” in *Proc. 3rd Annual IEEE Communications Society on Sensor and Ad Hoc Communications and Networks*, pp. 286–295, Sep. 2006.

[2] P. Liaskovitis and C. Schurgers, “Energy consumption of multi-hop wireless networks under throughput constraints and range scaling,” *Mobile Computing and Commun. Review*, vol. 13, no. 3, pp. 1–13, 2009.

[3] J. Zhu, C. Qiao, and X. Wang, “On accurate energy consumption models for wireless ad hoc networks,” *IEEE Trans. Wireless Commun.*, vol. 5, no. 11, pp. 3077–3086, Nov. 2006.

[4] J. Gomez and A. Campbell, “Variable-range transmission power control in wireless ad hoc networks,” *IEEE Trans. Mobile Computing*, vol. 6, no. 1, pp. 87–99, Jan. 2007.

[5] S. Singh and C. Raghavendra, “Pamas—power aware multi-access protocol with signalling for ad hoc networks,” *ACM Computer Commun. Review*, vol. 28, pp. 5–26, 1999.

[6] A. Misra and S. Banerjee, “MRPC: maximizing network lifetime for reliable routing in wireless environments,” in *Proc. IEEE Wireless Communications and Networking Conference (WCNC’02)*, pp. 800–806.

[7] C. Toh, “Maximum battery life routing to support ubiquitous mobile computing in wireless ad hoc networks,” *IEEE Commun. Mag.*, vol. 39, no. 6, pp. 138–147, June 2001.