Energy-Efficiency of Multihop Ad-hoc Sensor Networks

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1. Introduction

Wireless ad-hoc sensor (microsensor) networks contain a large number of low-cost and low-power sensor nodes that can collaborate as a group. This capability enables applications to achieve high quality and fault tolerant sensing networks with larger coverage area than conventional sensing networks [1]. Since sensing applications generate a large quantity of data, these data must be fused or aggregated to lower the energy consumption. There are many tight constraints in the design of sensor networks such as small size, light weight, low energy consumption and low cost. Among these, energy-efficiency should be considered as one of the most important issues since it is impossible to replace batteries on thousands of sensors considering the fact that these sensor networks are deployed in remote or inhospitable environments such as military command control, intelligence and tracking systems [1]. A wireless sensor network generally consists of a base station that can communicate with a number of wireless sensors via a radio channel. Data is collected at the sensor node and transmitted to the base station directly or through other nodes (multihop data transfer). Typically, a sensor node consists of one or more sensing elements (ultraviolet, temperature, humidity, etc.), data processing unit, communicating components and a power unit (battery). Conventional low power design techniques and hardware architectures only provide point solutions which are insufficient for these highly energy constrained systems. Energy efficiency, in the case of sensor networks, is far more complex, since it involves not only reducing the energy consumption of a single sensor node, but also maximizing the lifetime of an entire network. Network lifetime can be improved to a great extent by incorporating energy-awareness at the node and network level (see Section 6).

Communication protocols highly affect the energy-efficiency of sensor networks. Thus, designing an energy-efficient protocol is a requirement for prolonging the network lifetime. Among the existing communication protocols, those that exploit multihop routing to transfer the data to the base station are in the interest of several researchers. Such researches either propose different communication protocols based on multihop routing to reduce the energy usage of the network or they deal with the problems that arise when multihop routing is utilized such as the energy hole problem [2].

Generally, the energy for communication can be divided into three main components: 1- the energy that is consumed to transmit a packet 2- the energy consumption in order to receive a packet at the receiver node and 3- the energy consumption for idle listening to the channel [6,7,8,9,10,11]. It should be noted that smart designs for physical, MAC and network layers can improve each of the three mentioned components in terms of energy consumption [12,13,14,15]. Accordingly, in this project, we have investigated the effect of multihop routing especially for the protocols that operate at 2.4 GHz carrier frequency. The analysis of our experiment and simulation results can affect the routing decisions in routing protocols so as to decrease the total energy consumption of the entire network. Typically, we consider ANT wireless [3] and ZigBee [4] as the communication protocols.
Two experiments have been performed to measure the ratio of receive energy to transmit energy in ANT wireless protocol. Based on the experiments, three types of simulations have been carried out in the MATLAB environment to simulate a larger network with several hops. Results of our experiments show that the receive cost is higher than the transmit cost, therefore, energy waste in the multihop routing is anticipated. As for simulations, The results show that for 915 MHz carrier frequency (e.g., the protocol that MICA2 motes exploit to send the data) multihop routing is beneficial. However, as expected, for both 2.4 GHz protocols (ZigBee and ANT), sending data over a single hop achieves lower energy consumption.

2. Related work / Background

In wireless ad-hoc sensor networks, apart from issues like scheduling, topology control, node deployment and node locating, other key concepts in the form of energy consumption and network lifetime should be considered as the most critical issues since it is impossible to replace batteries on thousands of sensors. These critical issues attracted much attention in last few years. Consequently, many works exist that take these issues into account in designing communication protocols, MAC protocols and physical layer; Calhoun, et al. present novel approaches for improving the energy-efficiency of both digital and analog components of a sensor node like ADC and the transmitter [15]. Power-aware sensor node architecture and a battery-aware task scheduling algorithm using both dynamic voltage scaling and reverse body biasing techniques have been introduced in [34]. In this manner, the computation power (dynamic and static) of a sensor node has been reduced significantly. As for MAC layer schemes, an energy-efficient media access control (MAC) protocol called S-MAC is described in [40]. Investigators in [18], propose a cost-aware MAC protocol in which they consider the cost correlation among nodes to drive the channel contention and elect a node with a small cost as the multihop relay. A MAC protocol called SyncWUF was presented by Shi and Stromberg in [19] that achieves the best performance in respect of the energy consumption/latency trade-off for asynchronous, low to moderate traffic in wireless sensor networks.

As the energy consumption for transmitting one bit of data through the wireless channel is similar to thousands of cycles of instructions [20], in wireless sensor networks, energy consumption for computation is negligible relative to the energy consumption for communication. Figure 1 suggests that most of the communication energy is due to transmission and receive process. Furthermore, in order to be accurate, one should take into consideration the energy consumption for idle listening to the channel as well.

![Figure 1. Main energy consumers in a typical wireless sensor node.](image-url)
There has been a number of researches to find the receive energy to transmit energy ratio. According to [29], receive:transmit ratio is 1.05/1.4 by measurement, while more recent studies report ratios of 1:2:2.5 and 1:1.2:1.7 for idle:receive:transmit. The recent works stress the importance of the energy due to idle listening to the channel. Hence, putting as many nodes as possible to sleep is a smart way to significantly reduce the energy usage.

3. Preliminaries

This section presents some assumptions that have been made regarding the communication schemes throughout this project. In addition, this section introduces the radio energy model that was used in our experiments and simulations. The energy model takes both transmit and receive energy into account.

3.1. Network Assumptions

In this work, for a sensor network the following assumptions have been made:
1) All sensor nodes are identical and are stationary after deployment. Each node is assigned a unique ID, network number and transmission type.
2) Nodes have power control ability. As an example, MICA2 motes support ten different transmission energy levels. Each of these levels can be used to save energy. As another example, ANT motes can handle 6 different transmission power levels (-30 dBm up to 0 dBm) in order to save energy.
3) In our experiments, we found that the maximum transmission range for ANT wireless is 20 meters in case of line of sight transmission (the transmitting and receiving antennae can see each other). However, the nominal transmission range is 30 meters.
4) Likewise in ZigBee, the nominal transmission range is 100 meters while the maximum achieved line of sight transmission is 75-80 meters [21,22,23,24].

3.2. Energy model

The radio model we used in this project to measure the energy dissipation is the same as [30] in which \( E_{elec} \) is the energy being dissipated to run the transmitter or receiver electronics to transmit or receive one bit of the data packet. \( \epsilon_{amp} \) is the energy dissipation of the transmission amplifier to deliver one bit of data destined node who is \( d \) meters away (Figure 2).

Energy consumption for the receiver and transmitter is calculated as follows:

\[
E_{TX}(l, d) = lE^{TX}_{elec} + l\epsilon_{amp} d^n = lE^{TX}_{elec} + E^{RF}_{RF} \\
E_{RX}(l, d) = lE^{RX}_{elec}
\]  

(1)
above $l$ is the length of the transmitted/received message in bits, $d$ is the distance between transmitter and the receiver node and $n$ is the path loss exponent which is two for the free space model and is four in multipath model (generally $n$ lies in the interval [1.5,6]). We can observe that the transmitter dissipates energy to run the radio and power amplifier, while the receiver only expends energy to run the radio electronics. In this project we assume free space model ($n = 2$, $\epsilon_{\text{amp}} = \epsilon_{fs}$) for transmissions between nodes which is in accordance with the previous work [30] [31].

4. Receive to transmit ratio

In this section we present our experiment setup to measure the energy consumption of an all-time transmitting node and an all-time receiving node. Figure 3 shows our experiment setup.

Figure 3. Experiments to measure receive energy to transmit energy ratio.

In the experiments, two ANT motes were put $d$ meters away from each other in Boelter Hall’s third floor hallway so that the nodes can see each other. To measure the battery capacity more accurately, we equip the ANT motes with new Lithium coin cell batteries of type C2032. In the experiments, node A continuously sends data to node B. In order for the battery level to go down fast, the message rate has been set to the maximum possible safe message rate which is 200 messages per second. B is programmed to avoid sending acknowledgements. Therefore, A only transmits and B only receives the transmitted message from A. In the beginning of the communication, a number of setup and control messages exchange between the nodes. However, since the number of the mentioned messages is negligible relative to the total number of transmitted messages in the experiment, they are not taken into consideration in calculation of the consumed energy. It should be noted that except for the processor (MCU), all other parts of the ANT motes (ADC and the sensing component) have been deactivated to achieve a more precise estimation of the total energy consumption at each node.

The ANT MCU is TI’s MSP430f22 mixed signal microcontroller which embedded with the ANT wireless protocol. It provides the analog and digital inputs and outputs, serial interface to the host MCU and a wireless sensor platform called SensRcore.

Figure 4 shows the discharge trend of a coin cell battery of type C2032 (voltage versus time). The discharge trend has three phases. First it follows a linear behavior, afterwards for most of the remaining capacity the discharge fashion is flat and the third phase again shows a linear degradation with time. It should be noted that the total battery capacity of C2032 is 220 mAh. The slope of the discharge line (first phase) corresponds to transmit energy of node A and likewise, it corresponds to the receive energy of node B.
The following equation, relates the time to the used battery capacity. The denominator contains two terms. The first term called base_current mostly stems from the processing power. According to the datasheet the base current is equal to 32 µA. However, the second term represents the communication power which is directly proportional to the message rate.

\[
\text{time} = \frac{\text{Battery capacity [mAh]}}{\text{Base current [µA]} + (\text{Energy TXorRX [µAs]} \cdot \text{Message Rate [Hz]} \cdot \frac{1}{s})} \quad (2)
\]

In both experiments, we derive the value of Energy_TX or Energy_RX for nodes A and B, respectively. To be more specific, the energy consumption for transmitting a single message in node A and for receiving a single message in node B will be calculated to be used in the MATLAB simulations presented in Section 5.

4.1. First experiment

This experiment has been carried out twice for two different cases where the distance between the two nodes are the minimum and maximum values for ANT wireless protocol. (Minimum distance implies that the minimum transmission energy has been used in the transmitter).

In the first experiment, node B was put 1 meter away from node A (d = 1 m). In this experiment, for node A it takes 234 minutes to consume 10 units of its battery capacity. While, for node B it takes 125 minutes to use up the same amount of its battery capacity. It should be noted that having the distance of 1 meter in this experiment, implies that the minimum transmission energy has been used in the transmitter to convey (broadcast) the message to its proximity (-30 dBm according to the datasheet). Substituting the values for time, current, capacity, and message rate into (2), the transmit and receive energy will be as follows:

Node A: Transmit Energy = \(\text{Energy_TX} = 12.7 \mu\text{As}\) \quad (3)

Node B: Receive Energy = \(\text{Energy_RX} = 23.9 \mu\text{As}\) \quad (4)
Accordingly, the receive to transmit energy ratio can be found:

\[
\frac{\text{Receive Energy}}{\text{Send Energy}} = 1.88 \quad (5)
\]

The ratio of 1.88 is as expected. Since, the term \(E_{RF}\) in (1) is negligible comparing to the distance-independent term \(lE_{elec}\).

4.2. Second experiment

In the second experiment, node B resides 20 meters away from node A \((d = 20 \text{ m line of sight})\). Similar to the first experiment, for node A, it takes 180 minutes to consume 10 units of its battery capacity. While, for node B it takes 130 minutes to consume the same amount of its battery capacity. Having the distance of 20 meters in this experiment implies that the maximum transmission energy has been used in the transmitter to broadcast the message to distance of 20 meters away.

The energy consumption, similar to the previous experiment, can be derived:

\[
\text{Node A: Transmit Energy} = \text{Energy}_{TX} = 16.5 \mu\text{As} \quad (6)
\]
\[
\text{Node B: Receive Energy} = \text{Energy}_{RX} = 23 \mu\text{As} \quad (7)
\]

Accordingly, the receive to transmit energy ratio can be found:

\[
\frac{\text{Receive Energy}}{\text{Send Energy}} = 1.39 \quad (8)
\]

As it can be seen, the ratio of 1.39 shows that although the ANT transmitter (Nordic nrf24L01 [32]) uses its maximum power to send the message, the receive energy is still higher than the transmit energy.

5. Simulation of multihop schemes

In this section, the performance of different wireless communication protocols in terms of energy-efficiency has been simulated in the MATLAB environment. Table 1 summarizes three wireless technologies and their representative mote that have been simulated to evaluate the energy consumption of multihop schemes.

<table>
<thead>
<tr>
<th>Mote</th>
<th>MICA2 [40]</th>
<th>MICAZ [40]</th>
<th>ANT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Frequency</td>
<td>915 MHz</td>
<td>2.4 GHz</td>
<td>2.4 GHz</td>
</tr>
<tr>
<td>Transceiver</td>
<td>CC 1000 (Chipcon)</td>
<td>CC 2420 (Chipcon)</td>
<td>nrf24L01 (Nordic)</td>
</tr>
<tr>
<td>Receive to Transmit Energy Ratio</td>
<td>0.38</td>
<td>1.13</td>
<td>1.39</td>
</tr>
<tr>
<td>Transmission Range</td>
<td>305 meters</td>
<td>75-80 meters</td>
<td>20 meters</td>
</tr>
<tr>
<td>(E_{elec}^{TX})</td>
<td>50 nJ/bit</td>
<td>129 nJ/bit</td>
<td>22.5 nJ/bit</td>
</tr>
<tr>
<td>(E_{elec}^{RX})</td>
<td>50 nJ/bit</td>
<td>144 nJ/bit</td>
<td>39.6 nJ/bit</td>
</tr>
<tr>
<td>(E_{amp})</td>
<td>10 pJ/bit/m²</td>
<td>28 pJ/bit/m²</td>
<td>28 pJ/bit/m²</td>
</tr>
</tbody>
</table>
The energy parameters related to ANT are calculated based on the experiment results of Section 4 as follows:

\[ E_{\text{elec}}^{\text{RX}} = 22\, \text{mA} \times 3 \, \text{volts} \times 600 \, \mu\text{sec} \times \frac{1}{1000 \, \text{bits}} = 39.6 \, \text{nJ/bit} \quad (9) \]

\[ E_{\text{elec}}^{\text{TX}} = \frac{39.6 \, \text{nJ/bit}}{1.88 \, \text{(receive to transmit ratio)}} = 22.5 \, \text{nJ/bit} \quad (10) \]

The physical message length for all three platforms is assumed to be 1000 bits.

According to the radio energy model presented in Section 3.2, the energy consumption for multihop communication in a one-dimensional network from the source to the base station across a distance \( d \) using \( h \) hops (see Figure 5.) is equal to:

\[ E_{\text{tot}}(l, d, h) = h(E_{\text{Tx}}(l, d / h) + E_{\text{Rx}}(l, h)) = h(lE_{\text{elec}}^{\text{TX}} + lE_{\text{amp}}^{\text{TX}}(d / h)^n + lE_{\text{elec}}^{\text{RX}}). \quad (11) \]

It can be inferred from (11) that multihop schemes outperform direct transmission schemes when the receive cost is negligible compared to the transmission cost which depends on the distance between the two nodes as well. Furthermore, the path loss exponent also affects the energy-efficiency of multihop; for larger values of path loss exponent, the transmission energy dominates the receive energy even for small distances. However, it should be noted that since the IC transceivers used in sensor nodes are not able to send the data with very high power (more than 0 dBm), therefore, changing the path loss exponent by changing the transmission environment would not change the maximum transmission power of sensor nodes (MICA2, MICAZ, and ANT).

Table 2 gives the values of path loss exponent for different transmission environments [13]. According to this table, the assumption of considering the path loss exponent of two for the hallway experiment is a reasonable assumption. More information regarding the relation of path loss exponent to the environment can be found in [13].

<table>
<thead>
<tr>
<th>Location</th>
<th>Path loss exponent lies in the interval:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apartment Hallway</td>
<td>[1.9,2.2]</td>
</tr>
<tr>
<td>Engineering I (UCLA)</td>
<td>[1.4,2.2]</td>
</tr>
<tr>
<td>One-Sided Corridor</td>
<td>[1.4,2.4]</td>
</tr>
<tr>
<td>One-Sided Patio</td>
<td>[2.8,3.8]</td>
</tr>
<tr>
<td>Sandy Flat Beach</td>
<td>[3.8,4.6]</td>
</tr>
</tbody>
</table>

5.1. Simulation of multihop routing on MICA2 motes (915 MHz)

In the first simulation, the energy parameters related to the MICA2 mote, which operates at 915 MHz are considered. As Figure 6 suggests, for distances above 72 meters, using two
hops instead of a single hop (direct transmission), the network will end up being more energy-efficient. This is because, beyond this point, the distance-dependent term in the energy model equation (equation (11)) becomes dominant. Likewise, for transmission distances above 135 meters, having 3 hops would yield a better performance in terms of energy-efficiency. It should be noticed that since the transmission range for MICA2 mote is about 300 meters, one can take advantage of multihop routing in a wireless sensor network that uses MICA2 as its sensor node.

Figure 7 graphs the energy consumption per bit for transmitting the data to a destination that is 1000 meters away. According to the graph, the optimal number of hops for this network is 7-8 hops. This means that to achieve the best energy-efficiency, one has to send the data over 7-8 hops.

![Distance dependent term becomes dominant](image1)

Figure 6. Energy consumption of multihop routing for different distances using 1-4 hops using MICA2 motes.

![Energy consumption for transmitting a single message 1000 meters away using intermediate MICA2 motes](image2)

Figure 7. Energy consumption for transmitting a single message 1000 meters away using intermediate MICA2 motes.

5.2. Simulation of multihop routing on MICAZ motes (2.4 GHz)

In the second simulation, using the energy parameters of MICAZ mote (see Table 1), operating at 2.4 GHz frequency, the multihop routing scheme to transmit a single message to the receiver node with different distances from the sender node, has been simulated for
different number of hops. As it can be seen in Figure 8, for distances above 180 meters, two-hop transmission outperforms direct transmission scheme in terms of total energy consumption. Nevertheless, due to the fact that the maximum transmission range of ZigBee is 75-80 meters, in practice, multihop routing is not beneficial in terms of energy-efficiency. Based on the graphs of Figure 8, one can claim that in the sense of energy consumption, direct transmission works more efficiently as compared with multihop routing.

5.2. Simulation of multihop routing on MICA2 motes (915 MHz)

5.3. Simulation of multihop routing on ANT motes (2.4 GHz)

As with ZigBee, the process of sending a single message has been simulated assuming that the network contains ANT motes. The simulation has been carried out for data transmission over different number of hops. The distance between the sender node and the receiver node varied between 0 and 300 meters. Figure 9 illustrates the energy consumption versus the distance that the message travelled either through direct transmission or multihop routing. As it can be seen, since the practical transmission range of ANT wireless is 20 meters, sending the data over multiple hops would not be beneficial in the sense that the receive cost always dominates the total energy consumption of the network for the practical transmission range of the protocol. This situation can be attributed to the fact that the receive energy to transmit energy ratio in this protocol is relatively high (1.39).

6. Discussions

Since the path loss of radio transmission scales with distance in a super linear fashion, the transmission energy \( E_{RF} \) can be reduced by dividing a long path into several shorter ones. However, if the number of intermediate nodes is large then the energy consumption per node is dominated by the terms \( E_{elec}^{TX} \) and \( E_{elec}^{RX} \). Hence, an optimum for the number of hops exists. Figure 10 shows that when the carrier frequency of wireless technology increases, the receive energy becomes more substantial. In wireless communication protocols that operate at 2.4 GHz such as ZigBee and ANT, the receive cost completely dominates the transmission cost. This implies that in these protocols direct transmission routing outperforms multihop routing.
in terms of energy-efficiency. This can be attributed to the complexity of receiver circuit in high frequencies which stems from more complex and faster mixers and synthesizers in the receiver circuit at high frequencies. In other words, although increasing the carrier frequency implies a smaller antenna which is desirable, it increases the complexity of the receiver and hence, the energy consumption of the receiver node.

Another factor that affects the receive energy is the receive time. That is, the turn-on time of the receiver in order to receive the newly arrived data. In ANT the receive time is significantly lower than the receive time in ZigBee. Accordingly, the receive energy in ANT is appreciably smaller than the receive energy of ZigBee (39.6 nJ/bit versus 144 nJ/bit).

Figure 9. Energy consumption of multihop routing for different distances using 1-5 hops using ANT motes.

Figure 10. Receive energy versus transmit energy for different wireless technologies.
Apart from the fact that multihop routing is not useful when the receive energy is comparable/larger than transmit energy, other drawbacks of multihop schemes that one should consider are: 1- high delays 2- more complexity in routing decisions 3- energy consumption due to overhearing and 4- low network throughput. [33] lists other downsides of the multihop routing to prove that multihop approach is not as beneficial as it seems to be.

The results of this project affect the routing decisions in cluster-based communication protocols such as LEACH [12] and especially its successors [41]. As Figure 11 indicates, a cluster head far away from the sink (base station) use the closer cluster heads to relay its data to the base station. However, according to our experimental results, in many cases it is better that the intermediate cluster heads send the data that they received from the outer space directly to the base station [25,26,27,28]. This way, a huge amount of energy could be saved. One approach to this problem is to assign a probability to each intermediate cluster head which determines whether it sends the data directly or it plans to send the data to a closer cluster head (e.g., to balance the energy load among all the nodes across the network).

Although the applied energy model in this project is widely-used among several researches [34,18], a more powerful energy model should be considered in the future. Generally, a complete flawless energy model should take into account the effect of data rate, modulation scheme, number of wireless channels, nearby nodes (overhearing energy), the sensitivity of the receiver, channel condition (path loss exponent), packet size, and probability of collision [35,36,37,38,39].

One other criticism of our approach is that it does not separate the energy due to idle listening to the channel from the receive energy which introduces some error in the experiments. This also relates to the energy model that was used in the project.

![Figure 11. An example of cluster-based routing (Nodes send their data to their cluster head and cluster heads have the closer cluster heads relay their data to the sink (base station)).](image)

7. Conclusions

The multihop routing for wireless ad-hoc sensor networks forces a node to seek data transfer to the BS by finding one or multiple intermediate nodes. The data packets from the source node are relayed among the intermediate nodes until they reach the destination. The main advantage of this approach is that the transmission energy consumption may be reduced to a great extent. However, more investigation is required to find the efficacy of multihop
routing for current customized communication protocols for ad-hoc sensor networks such as ANT and ZigBee.

In this project, two experiments have been performed to measure the energy parameters of ANT wireless protocol, namely, receive energy and transmit energy. Based on the experiment results and using our MATLAB simulator, multihop schemes on ad-hoc sensor networks with three different motes (MICA2, MICAZ, and ANT) have been evaluated in terms of energy consumption. In the simulations, both the size of the network (distance between the sender and the ultimate receiver) and the number of hops have been varied.

Based on the simulation results, for ANT and ZigBee, multihop approach would not decrease the total energy consumption of the network and should be avoided unless the receiver node is out of reach. However, simulation results show that in protocols that exploit lower frequencies such as the communication protocol used in MICA2, it is worth using multihop routing. This is mainly due to the fact that the maximum practical transmission range is significantly higher than that for ANT and ZigBee.

8. References

[32] [32] Nrf24ap1, Single chip 2.4GHz nRF24XX Transceiver with Embedded ANT Protocol, Nordic Semiconductor ASA.
[40] MICA, MICA2, and MICAZ: Katarzyna Bilinska, Marcin Filo, Rafal Krystowski