Experimental Study of Energy Consumption in Direct Transmission and Multi-hop Transmission for Wireless Sensor Networks

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Abstract

How to prolong the lifetime of Wireless Sensor Networks (WSNs) is one of the primary challenges when design and deploy WSNs. Following our previous theoretical and numerical work, we mainly focus on studying the relationship between energy consumption and hop number from an experimental point of view in this paper. Actually, the importance of hop number to the energy consumption is commonly neglected by most routing protocols and a considerable amount of energy can be saved if the relationship between them were carefully studied. A considerable amount of experiments have been made to study the practical design parameters under practical sensor network environment. We validate our judging criteria of transmission manner and transmission radius from both theoretical and experimental aspects. Also, energy aware multi-hop transmission is thoroughly studied so that it lays a solid foundation for our future research.

Keywords: Energy Consumption, Routing, Multi-hop, Wireless Sensor Networks.

1. Introduction

Wireless Sensor Networks (WSNs) are composed of hundreds or thousands of tiny and inexpensive sensor nodes, which can effectively monitor their surrounding environment through sensing, data processing and communication. They have a variety of applications, such as military surveillance, industry monitoring, mass vehicle control and smart home etc [1].

One of the challenges to the successful WSNs application is the energy consumption problem. It can be further divided into three sub-components, namely: the energy consumption during sensing, processing and communication parts. In this paper, we just focus on the energy consumption during the process of communication since it plays a dominating role among three of them.

Currently, numerous works have been done to improve the routing performance in the network layer of WSN. [10] presents a taxonomy about most of the routing protocols for WSN and it categorizes them into three main classes, which are Data-centric [2, 3], Hierarchical [4, 5, 6] and Location-based [7, 8] routing protocols.

Data aggregation (a.k.a. data fusion), is an important technique adopted by the data-centric routing protocols [2, 3]. It can reduce the energy consumption during communication process due to the fact that many nearby sensor nodes might sense and collect similar information. Consequently, there is more or less similarity among those collected sensor data. Through this method, both the size and the number of transmission can be reduced largely. However, the computational complexity will also increase since data aggregation method is introduced therein.

Hierarchical routing protocols [4, 5, 6] have gained quite amount of attention in recent years. The key idea is that the whole network can be further divided into smaller areas which are called clusters. In each cluster, there is a cluster head which functions like a Base Station (BS). Within each cluster, each node just communicates with the cluster head in a short range. And the cluster heads communicate with each other to transmit their collected data to the remote BS (also called sink node), which is usually far away from the monitored environment. In this way, resources like spectrum or channel can be more efficiently utilized and load can get more balanced through the rotation of cluster head. Also, data aggregation can be done by the cluster head in a more efficient way. More importantly, the energy consumption can be greatly reduced since the communication range is largely reduced and the ordinary sensor nodes within one cluster can be put into sleep state according to a Time Division Multiple Access (TDMA) schedule, which is sent by cluster head. The disadvantage is that the clustering algorithms need to be carefully designed so that other performance parameters, such as packet delivery ratio, latency, might not get deteriorated.

In the location-based routing protocols [7, 8], sensor location information is gained either by GPS devices or some complex algorithms based on received signal strength. The GSP devices will also consume a non-neglectable amount of energy. The advantage is that blind flooding is not necessary and the communication overhead is largely reduce, so the energy consumption can also get reduced consequently.

Among all these routing protocols, the data is either routed by cluster head or based on certain algorithms, such as shortest-path algorithm, lowest-id algorithm or some probabilistic algorithms. Usually, the hop number plays a secondary role and its influence to energy consumption is almost neglected in most of these protocols. So, we primary study the relationship between hop number and energy consumption from an experimental point of view in this paper, after our prior theoretical and numerical work in [11]. Later on, we can do further simulation and comparison based on various scenarios.

The main contribution in this paper is that we make extensive experiments and study of several important design parameters from a practical application aspect. We provide the distance threshold when selecting transmission manner. Also, we thoroughly explore the successful rate of selecting multi-hop transmission rather than direct transmission. The influence of network density as well as node transmission radius is also carefully studied and compared in this paper.

2. Background Knowledge

2.1 Network Model

Table 1 lists most of the relevant network parameters and their definitions used in this paper.

Table 1. Network parameters

Parameter	Definition	Unit
[X, Y]	Network range	[300,300] m^2
N	Total number of nodes	[200, 500]
n_i	The ith node	$(1 \le i \le N)$
R	Transmission range of each node	[20, 40] m
d_{ij}	Distance from n_i to n_j	m
BS	Position of Base Station	[150, 150]

2.2 Basic Assumptions

i) All sensor nodes are assumed to be homogenous and stationary;

ii) The energy consumption of sensing and processing is not considered here;

iii) Only BS has location knowledge about all nodes.

Unlike some of the recent work [12, 13], there is no sensor node which is supervisor to the others so that it can be continuously used as special relay node or cluster head. Also, we do not consider data aggregation and energy consumed during sensing and processing here. Because the energy consumed during communication process plays a dominating role among three of them. The ordinary sensor nodes are unaware of their location and only BS has global information about all the sensor nodes through certain algorithms, such as signal attenuation and directional estimation algorithms etc.

2.3 Energy Model

A commonly used energy model is known as first order radio model [4, 5]. Table 2 gives the related parameters, their definitions as well as the specific values used in this paper. Like the other papers, we also assume an d^2 energy loss during transmission and let $E_{Tx-elec} = E_{Rx-elec} = E_{elec}$, $E_{Tx-amp} = \varepsilon_{amp}$. So, to transmit a l -bits message over a distance d , the radio expends:

$$E_{Tx}(l,d) = E_{Tx-elec}(l) + E_{Tx-amp}(l,d) = l * E_{elec} + l * \varepsilon_{amp} * d^2 \quad (1)$$

and to receive this message, the radio expends:

$$E_{Rx}(l) = E_{Rx-elec}(l) = l * E_{elec} \quad (2)$$

and to forward this message by an intermediate node, the radio expends:

$$E_{Fx}(l,d) = E_{Tx}(l,d) + E_{Rx}(l) = 2l * E_{elec} + l * \varepsilon_{amp} * d^2 \quad (3)$$

Table 2. Radio parameters

Parameter	Definition	Unit
E_{elec}	Energy dissipation rate to run the radio	$50 nJ / bit$
ε_{amp}	Energy dissipation rate to run transmit amplifier	$100 pJ / bit / m^2$
l	Data length	2k bits
d	Transmission range	m

3 Mathematical Analysis of Energy Model

3.1 Direct Transmission or Multi-hop Transmission

Figure 1 shows a linear network where the distance between each node is r and there are n nodes equally placed on a one dimensional network. Works in [4] has proved that:

Direct transmission consumes less energy than multi-hop transmission if:

$$\frac{E_{elec}}{\varepsilon_{amp}} > \frac{r^2 * n}{2} \qquad (4)$$

Since $d = n * r$, formula (4) can be re-formulated as:

$$\frac{E_{elec}}{\varepsilon_{amp}} > \frac{r^2 * n}{2} = \frac{d^2}{2 * n} \qquad (4\text{-}1)$$

Let:

$$n_e = \frac{\varepsilon_{amp} * d^2}{2 * E_{elec}} \qquad (5)$$

when direct transmission consumes the same energy as multi-hop transmission. Formula (5) gives us a very important judging criterion during the selection of transmission manner as well as optimal hop number during multi-hop transmission. The interested readers can refer to [11] for more information.

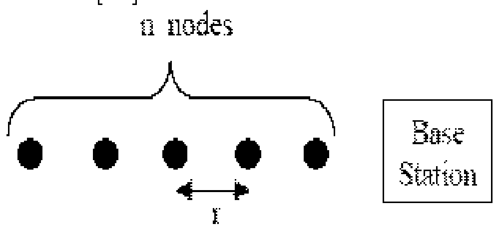

Figure 1. Simple linear network

3.2 Optimal Hop Number

Suppose $l = 1$ bit, the energy consumption during direction transmission will be:

$$E_1 = E_{elec} + \varepsilon_{amp} * d^2 \qquad (6)$$

For multi-hop transmission, the corresponding energy consumption will be:

$$E_2(n) = E_{elec} + \varepsilon_{amp} * r^2 + (n-1)(2 * E_{elec} + \varepsilon_{amp} * r^2) = 2n * E_{elec} + \frac{\varepsilon_{amp} * d^2}{n} - E_{elec} \qquad (7)$$

It is easy to prove that E_2 has a minimum value Min.$(E_2) = (4n^* - 1)E_{elec}$ when:

$$n = n^* = \sqrt{\frac{\varepsilon_{amp}}{2 * E_{elec}}} * d \qquad (8)$$

Here, n^* is the optimal hop number during multi-hop transmission. Recall formula (5), we can draw another important conclusion which is: $n^* = \sqrt{n_e}$.

Since n_e is obtained when direct communication consumes the same amount of energy as multi-hop transmission, we can easily prove $E_2(1) = E_2(n_e) \geq E_2(n^*)$, as is shown in Figure 2. Finally, we can see that the corresponding multi-hop optimal distance:

$$d^* = \frac{d}{n^*} = \sqrt{\frac{2 * E_{elec}}{\varepsilon_{amp}}} \qquad (9)$$

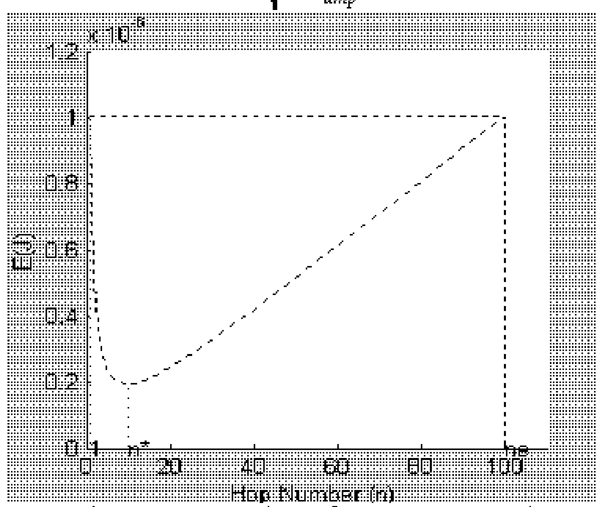

Figure 2. Comparison of energy consumption

4. Simulation Results

4.1 Study of Distance Threshold

Figure 3 gives an ordinary random deployed sensor network topology. Recall formula (5) and let $n_e = 2$, we can get $d_T(n_e = 2) = \sqrt{4 \cdot E_{elec} / \varepsilon_{amp}} \approx 44.7$, which is the smallest circle in Figure 3. If the distance $d < d_T$, direct transmission will be superior to multi-hop transmission according to the formula (4-1). On the other hand, when $d > d_T$, multi-hop transmission could be more energy efficient than direct transmission, depending on the practical network topology.

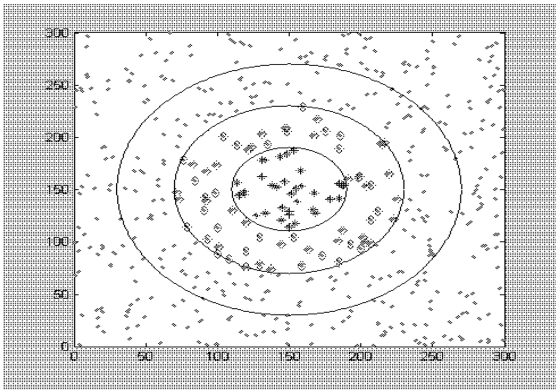

Figure 3. Sensor Network topology

However, formula (4) to (5) only hold true for the ideal one dimensional simple linear network situation, as is shown in Figure 1. As for the practical sensor network environment, they might not hold true since the sensor nodes are usually randomly deployed in the real sensor network. That is why we need to do extensive experiments to validate the theoretical results and it is our main research motivation in this paper.

Table 3.1 and 3.2 provide us several practical cases of energy consumption, which is randomly selected from extensive simulation results. The network environment is the same as Table 1, where N=500, R=40. From Table 3.2, we can see that when $d < d_T$, direct transmission will always consume less energy than multi-hop transmission. When $d > d_T$, multi-hop transmission will be more energy efficient in most cases. However, it does not always hold true due to the network topology. Here, the distance threshold d_T gives us an importnt judging criterion about selection of transmission manner.

Table 3.1 Distance threshold parameters d_T

Parameter	Definition	Unit
d_0	Direct trans. distance	m
d_1	First hop distance	m
d_2	Second hop distance	m
E_1	Direct trans. energy con.	J
E_m	Multi-hop trans. energy con.	J

Table 3.2 Numerical study of distance threshold d_T

d_0	d_1	d_2	E_1	E_m
40	26	19	0.00042	0.00051
46	21	37	0.00052	0.00066
51	31	21	0.00062	0.00058
70	32	38	0.00110	0.00078

4.2 Study of Successful Rate

Once the real distance $d > d_T$, we will further study whether or not multi-hop transmission is superior to direct transmission under practical sensor network topology. For example, when d=46, there might not exist such an intermediate node with $d_1 = d_2 = 23$ so that multi-hop transmission is more energy efficient in real network. So, direct transmission will be more energy efficient than the 2-hop multi-hop transmission. In the following two sub-sections, we will study how the network topology influences the energy consumption for multi-hop routing.

First, the successful rate (SR) is defined as the ratio of energy efficient nodes over total involved nodes. Here, energy efficient nodes mean those nodes which can find at least one multi-hop route, which is superior to the direct transmission.

Table 4.1 and 4.2 show the simulation results as for the same network environment as previous su-bsection, where N=500, R=40.

Table 4.1 Successful rate parameters

Parameter	Definition	Unit
d_0	Distance from BS	m
S_2	2-hop trans. SR	%
S_3	3-hop trans. SR	%
S_0	Multi-hop total SR	%

Table 4.2 Numerical study of successful rate

	d_0	S_2	S_3	…	S_0
1	[45, 50]	53	0		53
2	[50, 60]	95	5		96
3	[60, 70]	90	50		95
4	[70, 80]	54	69		94
5	[80, 90]	0	94		95

Due to the variation of practical network topology, we average the final value over 10 different network topologies. From Table 4.2, we can see that 2-hop SR decreases as d_0 increases. In the mean time, higher hop SR increases. It is in accordance with Figure 2 and 3. When $d > 50$, SR is larger than 94%, which means that it could nearly always find an energy efficient multi-hop route instead of direct transmission route. The reason S_2 is smaller in [45, 50] is that d_0 is very small, so it would be very difficult to find an intermediate node, as is stated in the first paragraph in this section.

From Figure 4, we can find this trend more clearly. Here, the number 1 to 5 is corresponding to the d_0 in Table 4.2.

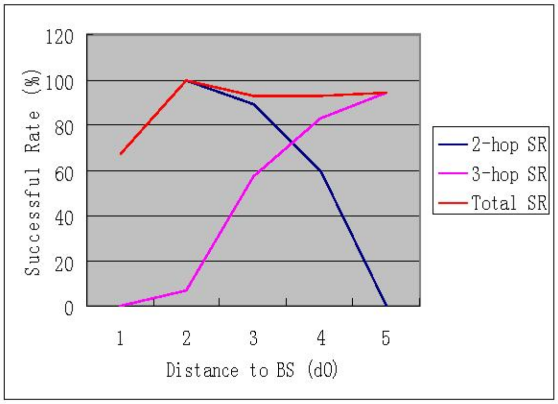

Figure 4. Successful rate for multi-hop transmission

4.3 Study of Total Node Number

As we know, the total node number and the node transmission radius are two important metrics which can determine the network topology. In this sub-bsection, we study the influence of total node number to the successful rate (SR) and we will study the influence of node transmission radius to SR in the next sub-section.

In the real network environment, we let N equal to 500, 400, 300, 200 and let $60 < d_0 < 70$. We also make 10 times for the same experiment and get the averaged value from them. Figure 5 shows the average value of successful rate (SR) for different N and the number 1 to 4 is corresponding to N=500 to 200 respectively.

From figure 5, we can see clearly that SR decreases as N decreases. In other words, when the network density is large, there will be more candidate sensor nodes which can find an energy aware route. So, the SR for multi-hop transmission will be higher than direct transmission. Actually, from our observation, the SR is approaching 100% when N is larger than 500.

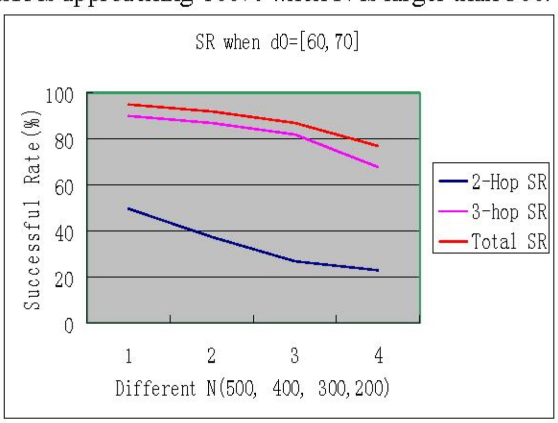

Figure 5. Successful rate for different N

4.4 Study of Transmission Radius

Finally, we will study the influence of transmission radius (R) to the successful rate (SR). Intuitively, if R is too large, it will consume more energy on average and it will not be energy efficient. Also, the number of neighboring nodes will be large and it will cause a larger routing table as well as a higher communication overhead. On the other hand, if R is too small, the optimal intermediate nodes in formula (8) might not be connected. So, there might be no energy efficient intermediate node and direct transmission will be superior over the multi-hop transmissions with a large number of intermediate nodes.

Table 5.1 Transmission radium parameters

Parameter	Definition	Unit
R	Transmission radius	m
S_2	2-hop trans. SR	%
S_3	3-hop trans. SR	%
S_0	Multi-hop total SR	%
n_2	Number of 2-hop route	
n_3	Number of 3-hop route	

Table 5.2 Numerical study of transmission radium

R	S_2	S_3	S_0	n_2	n_3
40	99	33	99	140	2147
30	62	31	75	51	265
20	0	3	3	0	3

From Table 5.2, we can see that the transmission radium can greatly influence the successful rate as well as the number of involved routes. It is worth noting that the number of involved routes increases exponentially rather than linearly with the radius. And the computational complexity would be very high if the related parameters are not carefully designed. Once again, this is the motivation of this paper.

Based on our theoretical analysis before, we provide a minimum radius bound d^* here. If $R \geq d^*$, optimal intermediate nodes are guaranteed to be found, as can be seen from formula (9). This is one important metric we deduce in this paper.

Fro the practical distance d, we can deduce another important metric as follows. When $d < d_T$, direct transmission is always better, and when $d > d_T$, the successful rate to find a multi-hop route increases as d increases. Especially, when the total node number is large enough, it would always be possible to find an energy efficient multi-hop route under the real randomly deployed sensor network.

5. Conclusions and Future Work

The comprehensive simulation and analysis in this paper is a following work after our theoretical and numerical work in [11]. Several important design metrics which can greatly influence the network topology are carefully studied from an experimental point of view, so that we can know when to choose direct transmission and when to choose multi-hop transmission based on the distance threshold. Also, we can determine the optimal hop number as well as the specific intermediate nodes from both theoretical and experimental results. So, the work in this paper lays a solid experimental foundation for our coming research.

In the near future, we will deepen our simulation by considering different routing scenarios, one of which is presented in [11]. Also, we will consider the case when BS is far away from the monitoring area, which is quite common due to safety or other consideration. Last but not the least important, we will make a comparison between our “hop-based energy aware routing (HEAR)” algorithm and other existing algorithms, such as shortest-hot algorithm, maximum remaining energy algorithm in the aspects of hop number, network lifetime etc.

Acknowledgements

This research was supported by the MIC (Ministry of Information and Communication), Korea, under the ITFSIP (IT Foreign Specialist Inviting Program) supervised by the IITA (Institute of Information Technology Advancement) and was supported by the MIC, Korea, under the ITRC (Information Technology Research Center) support program supervised by the IITA(IITA-2006-C1090-0602-0002).Professor Jinsung Cho is the corresponding author.

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