ENERGY EFFICIENCY OF MANY-TO-ONE COMMUNICATIONS IN WIRELESS NETWORKS

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ABSTRACT

This paper analyzes the energy consumption in a wireless network where communication occurs in a many-to-one fashion. The main motivation for this work comes from a large class of data-gathering wireless sensor networks. We consider and compare both flat and clustering network structures. We derive the ideal or minimum energy consumption required in both cases. We examine how the energy consumption is affected by the range of transmission of the nodes and the size of the area where the network is deployed. We also examine how the number of clusters affect energy consumption.

1. INTRODUCTION

In this paper we study the energy consumption of many-to-one communication in a wireless network. Our main motivation is the recent developments in wireless sensor networks. In many applications of these networks, data is gathered by multiple sensors at different locations and transmitted to a single sink where data can be stored and analyzed. The communication is thus naturally of the many-to-one type. It is important to note that although wireless sensor networks are our main motivation, our results and analysis apply to the more general cases of many-to-one communication in wireless networks.

We are particularly interested in two measures. One is the capacity of the network, defined as the maximum achievable per source data throughput, and the other is the energy consumed in the network when transmitting a given amount of data. Capacity has been studied in [1], [2] and [3] for peer-to-peer communication in a many-to-many scenario. In [4] the capacity in the many-to-one case is examined. In this paper we focus on the energy issue. These measures are affected by the characteristics of the network and by the way the network is organized. These include the size of the area the network occupies, the number of nodes in the network, the range of transmission of the nodes and the specifications of the transceivers used by the nodes. Possible organizations of the network include the flat and hierarchical organizations. In a flat organization all nodes act as peers in transmitting and relaying data for other nodes. In a hierarchical network, layers of clusters are formed. Nodes send their data to the cluster heads who then relay the data to either the higher layer cluster head or the sink (such as in [5]).

We will fix most of the characteristics of the the network, and compare the performance of the network using different organizations. We will allow the transmission range and the size of the network area to vary. A particular transmission range may not ensure connectivity of the network, thus we present our results as a function of this range.

The next section presents our network model. Section 3 gives our analysis of the network. The results are discussed in Section 4, and Section 5 concludes the paper.

2. NETWORK MODEL

We consider a randomly deployed network in a field of circular shape and radius R. The nodes are deployed uniformly over the field. There are $n = 1000$ nodes in the network. The sink is situated at the center of the network. Each node has one packet of length b bits to send to the sink. Thus each node has exactly one original transmission to perform in addition to relaying packets for other nodes.

We consider the energy consumed under ideal conditions, thus we assume that when a node is neither transmitting nor receiving, it would be asleep and does not waste any energy. Energy consumed in transmission is: $E_t(r) = (e_t + e_d r^{\alpha})b$, where e_t and e_d are specifications of the transceiver used by the nodes, and r is the transmission range used. Note that we do not consider power control, therefore for a given scenario r is fixed. b is the number of bits being sent. α depends on the characteristics of the channel. We consider a time invariant channel, thus α is constant. Energy consumed in receiving is $E_r = e_r b$. Again e_r depends on the transceiver used by the node.

In the case where the network is organized in a flat manner, the nodes transmit towards the sink. If the range is sufficiently large, it can reach the sink directly via a single hop. If this is not the case, then other nodes will serve as relays. In estimating the number of hops needed to reach the sink we consider the straight line from the node to the sink and divide it by r. This, along with the ideal conditions described above results in a lower bound on energy consumption.

In the case where the network is organized in a hierarchical manner, H extra nodes are inserted into the network to function

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as cluster heads. Each cluster has an area of $\frac{A}{H}$ where A is the area of the whole network. The clusters are also assumed to have a circular shape. Within a cluster, the nodes transmit to the cluster head in the same way as they do in a flat network. The cluster head has a range of transmission R so that it can relay the data in a single hop to the sink. Note that by selecting existing nodes as cluster heads instead of introducing extra node does not change our approach or conclusion.

The total energy we consider is the energy consumed in all transmissions and receptions by the nodes as well as the cluster heads (if applicable). It does not consider the energy consumed at the sink.

3. ANALYSIS

3.1. Flat Network

We begin by analyzing the energy consumption in the case where the network is organized in a flat manner. We will need to determine the number of transmissions and receptions done by the nodes and then apply the energy model discussed in the previous section.

Let x be the total number of transmissions required to deliver one packet from every node to the sink. Then $x - n$ is the number of received packets in the network. Note that n transmissions have the sink as the receiver. Since we do not consider the energy used at the sink, there are n less receptions than transmissions. The energy consumed is then:

$$E = x(E_t(r)) + (x - n)E_r. \tag{1}$$

To determine x, we consider the number of nodes that are h hops away from the sink, denoted by n_h. Because the nodes are uniformly distributed we have:

$$n_h = n\left(\frac{\pi}{A}h^2r^2 - \frac{\pi}{A}(h-1)^2 r^2\right). \tag{2}$$

For each one of the nodes that is h hops away the load or the amount of transmissions it has to perform, denoted by l_h, is:

$$l_h = \frac{\sum_{i=h}^{\lceil \frac{R}{r} \rceil} n_i}{n_h} = \frac{n(1-(h-1)^2\frac{\pi}{A}r^2)}{n_h}. \tag{3}$$

Thus we have:

$$x = \sum_{h=1}^{\lceil \frac{R}{r} \rceil} n_h l_h = \sum_{h=1}^{\lceil \frac{R}{r} \rceil} n(1-(h-1)^2\frac{\pi}{A}r^2). \tag{4}$$

In the above case the network consists entirely of sensing nodes, meaning each node not only relays data, but also generates data. Consider now a network with u nodes that generate data, and v nodes that act only as relays, both of them randomly deployed. Following the same reasoning as before, it is easy to see that the energy consumed is $E = y(E_t) + (y - u)E_r$, where $y = \sum_{h=1}^{\lceil \frac{R}{r} \rceil} u(1-(h-1)^2\frac{\pi}{A}r^2)$. Note that y only depends on u, not v. This means that if we have a network with n nodes and to that we add v nodes acting as relays, the minimum amount of energy consumed in the network does not change for a given transmission range. However, by introducing extra nodes, a smaller range of transmission is capable of ensuring connectivity. Depending on the size of the network area, this could be beneficial. The result obtained in this section will be plotted against r for different areas and discussed in the next section.

3.2. Hierarchical Network

We now analyze the energy consumption in the case where the network is organized in a hierarchical manner. We will proceed by determining the energy consumed in each cluster and then simply multiplying that by the number of clusters. Note that each cluster can be viewed as a flat network, thus much of our previous analysis can be applied. The difference is that we will also consider the number of transmissions and receptions that happen at the cluster head.

Let x_h be the number of transmissions performed by the nodes in a cluster. Note that all these transmissions have an intended receiver within the cluster, therefore the number of receptions is the same as the number of transmissions. Finally, in this case we add the energy spent transmitting the bits from a cluster head to the sink. This is done in a single hop, and the number of transmissions is $\frac{n}{H}$. The energy consumed in the network is:

$$E_H = (x_h(E_t) + x_h(E_r) + \frac{n}{H}E_t(R))H, \tag{5}$$

where

$$x_h = \sum_{h=1}^{\lceil \frac{R_H}{r} \rceil} \frac{n}{H}(1-(h-1)^2\frac{\pi}{A_h}r^2), \tag{6}$$

and R_H is the radius of the cluster area.

Intuitively we expect to use the above result to determine the number of cluster heads that minimizes the energy consumption. It turns out that as the number of heads grows, the energy consumption decreases. To see this, consider two identical networks, only in one H_1 heads are introduced, while in the other H_2 heads are introduced. Without loss of generality, assuming $H_1 < H_2$ and thus $R_{H_1} > R_{H_2}$, we have

$$E_{H_1} - E_{H_2} \geq 0 \tag{7}$$

To see this, one can show that this is equivalent to the following:

$$(E_t(r) + E_r)(H_1 x_{h_1} - H_2 x_{h_2}) \geq 0. \tag{8}$$

It is clear that $(E_t(r) + E_r)$ is non-negative. Therefore all we have to show is: $(H_1 x_{h_1} - H_2 x_{h_2}) \geq 0$. Using (8) we get:

$$\begin{aligned} H_1 x_{h_1} - H_2 x_{h_2} &= \sum_{h=1}^{\lceil \frac{R_{H_1}}{r} \rceil} n(h-1)^2 r^2 \left(\frac{1}{RH_2^2} - \frac{1}{RH_1^2}\right) \\ &+ \sum_{\lceil \frac{R_{H_2}}{r} \rceil + 1}^{\lceil \frac{R_{H_1}}{r} \rceil} n\left(1-(h-1)^2\frac{r^2}{RH_1^2}\right). \end{aligned} \tag{9}$$

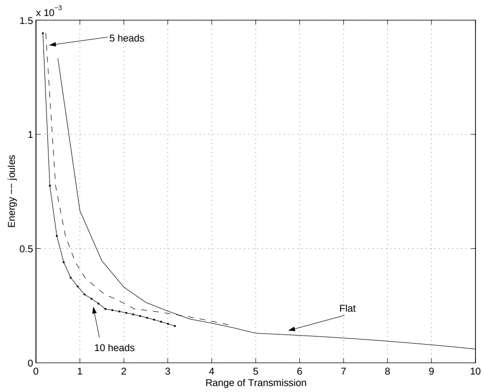

Figure 1: Radius=10

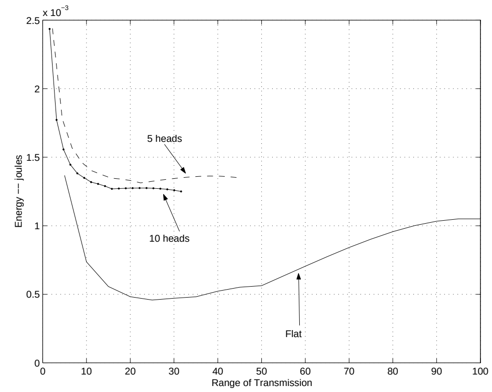

Figure 2: Radius=100

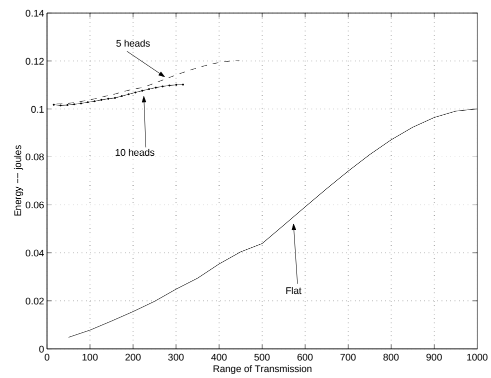

Figure 3: Radius=1000

The first term is clearly non-negative since $RH_1 \geq RH_2$. The second term is also non-negative since $h \leq \lceil \frac{R_{H_1}}{r} \rceil$. Therefore (9) holds. This means that as the number of heads increases, the energy consumed decreases. $H \leq n$ becomes the natural limit on the number heads as $H > n$ means some heads will be left unused. This result will be discussed in more detail in the next section. It is important to note that this result is only valid in an ideal scenario. In practice, since the nodes and the cluster heads are randomly distributed, the actual size of the cluster can be much larger than the expected size. Therefore the added heads may not always be an advantage.

4. DISCUSSION

In this section we plot and discuss the results obtained as a function of the range of transmission. In all our figures we used $e_t = 50\text{x}10^{-9}$, $e_r = 50\text{x}10^{-9}$, both in joules per bit, and $e_d = 100\text{x}10^{-12}$ joules per bit per meter squared. These values are taken from [5]. The hierarchical case was done with $H = 5$ and $H = 10$. α is set to 2.

Figures 1, 2 and 3 show the energy consumption of the flat network and the hierarchical network. Note that the range of r is smaller for the hierarchical networks than for the flat one. This is because in the flat network r can be as big as the radius of the network, but in the hierarchical network r is limited by the size of the cluster.

We see that when the size of the network area grows, the hierarchical network uses more energy than the flat network. This is because in the flat network the total distance the data travels in all cases is close to the straight line distance to the sink, while in the hierarchical network, data travels longer, since the data is first diverted to a cluster head. In a small area the effect of this diversion is minimal (Fig 1). However, in larger areas this diversion noticeably increases the energy consumption, shown in Figures 2 and 3. This does not mean that a flat network should always be used in networks with large area for scalability reasons. For example, it was shown in [4] that a better capacity can be achieved with a hierarchical network.

Changing the value of n would affect the energy consumed because the number of transmissions would change. However, the shape of the energy consumption curve in Figures 1, 2 and 3 would not change. It is the size of the network area and not the density of the network that is causing the change in energy consumption.

We have previously shown that the greater the number of heads, the lower the energy consumption. This is shown in all three figures. It may seem to contradict the fact that a flat network (where $H = 0$) performs better than a hierarchical one. Note that in the flat network the data is not diverted at all from its path towards the sink, while as soon as a single head is introduced, all data is diverted. As more heads are introduced, the distance to the closest heads tends to decrease and thus the effect of the diversion is lessened.

Another important point is that at small scales, e_t is the dominant part of the energy consumption, thus as r increases, the energy consumption decreases (see Fig. 1). At greater scales, as r increases the energy consumption increases because the dominant part of the energy consumption becomes related to the square of the distance, meaning that we are better off with many small hops than a few large ones (see Fig. 3). This is important because it is generally accepted that smaller hops are better than large ones when it comes to energy consumption, but what this shows is that that depends on the scale of the network.

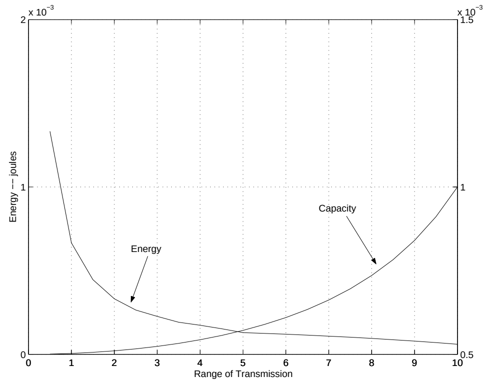

Figure 4: Flat network, R=10

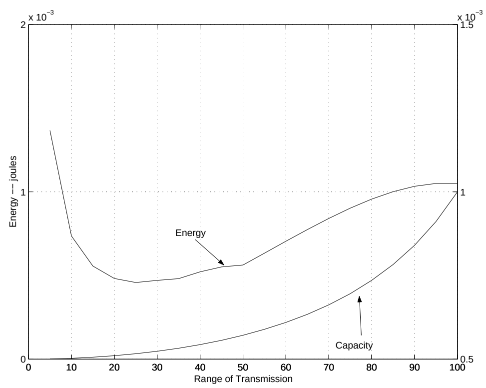

Figure 5: Flat network, R=100

It is worth pointing out that although we showed results for all r, not all r are adequate in a practice. In practice, one must choose r to be large enough to ensure the connectivity of the network. Previously we showed that a network with n data-generating nodes consumes the same energy as a network with n data-generating nodes plus v relays. Introducing the relays allows us to decrease the value of r necessary to ensure connectivity, i.e., this allows us to choose a transmission range toward the left of the curve.

Figures 4, 5, and 6 show the results for the energy consumption of the flat network (left Y axis) and the capacity that can be achieved in the same network (right Y axis). The capacity results are obtained from [4]. These results are important because we see that while energy consumption is affected by the scale of the network, this is not true for capacity. That means that the relation between energy and capacity changes as the scale of the network changes. In particular, we see that for small scales, the capacity increases as the energy consumption is decreased. Unfortunately, for large scales, the capacity increases only as the energy consumption increases. This creates a trade off of energy versus capacity at large scales.

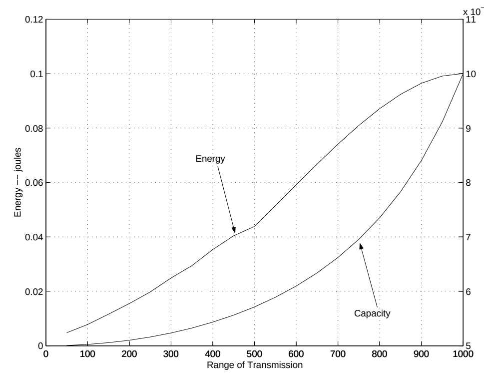

Figure 6: Flat network, R=1000

5. CONCLUSION

In this paper we have examined the ideal energy consumption of a many-to-one communication in a wireless network. We have shown that a flat organization of the network provides a lower energy consumption than a hierarchical organization in networks that occupy a large area. However this might not always be desirable because of capacity issues [4]. Also, when a flat network is used, the introduction of relay nodes does not increase energy consumption. This means that we can lower r which may be beneficial in some scenarios. When a hierarchical network is used, less energy is consumed as the number of heads increases. We proved that this hold true for networks of any size. We showed that the trade off between capacity and energy consumption only exists in networks that occupy large areas. In small areas, the energy consumption is reduced as the capacity increases.

6. REFERENCES

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