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A Study on the Energy Consumption of Cluster-based Multi-Hop Wireless Network

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ABSTRACT

The performance of wireless sensor networks is severely restricted by the energy limits of the nodes. Clustering is one approach to the reduction of energy consumption since it permits data aggregation (e.g. fusion and compression) and better control of the transmit power.

This paper studies the total energy consumption of the cluster approach. We assume a configuration in which nodes are deployed in a reticular pattern and all nodes can communicate with the gateway directly. We use two energy consumption models; I) a model based on a radio propagation formula (first-order radio model), and II) a model based on the existing Chipcon device CC1020. We then compare clustering to direct communication in terms of total energy consumption up to the gateway. We find that clustering based on CC1020 is not effective from the point of view of total energy consumption, whereas clustering based on first-order radio model is effective.

1. INTRODUCTION

In wireless sensor networks, sensor nodes have restricted performance and functionality; moreover, their battery capacity is very small. Therefore, it is important to reduce the energy consumed by each sensor node. Because radio circuits consume much energy when active, intermittent operation is necessary to reduce energy consumption and prolong the lifetime of the network. Multi-hop communication is also necessary to create widespread networks. To link nodes that work intermittently, timing of wake-up (and power-off), that is, timing of transmission and reception, must be synchronized between nodes. To achieve synchronized communication with low energy consumption and in a short period, the amount of data sent and received between nodes should be small.

The cluster configuration is thought to be a solution to this problem. The following benefits can be expected by adopting the clustering.

- Transmit power control and packet relay across short range links might reduce the total energy consumption spent on transmitting and receiving.
- With a cluster, there is the possibility of reducing the number of control packets compared to the flat topology.
- Data aggregation and compression/fusion on cluster heads is able to reduce the amount of data transmitted.

In other words, clustering might reduce the total energy consumption and realize efficient synchronized intermittent operation under the control of the cluster head. LEACH[1] is an architecture intended to realize long-life networks through the use of clustering.

The rest of this paper organized as follows. Section 2 describes the impact of clustering on energy consumption. Section 3 explains our radio models – first-order model and a model based on an existing radio device CC1020 used to calculate the total energy consumption. In Section 4, we explain our cluster and network model, and then we report the results. Finally, Section 5 concludes this paper.

2. ENERGY CONSUMPTION OF CLUSTERS

2.1. Relay Transmission

In wireless communication, receive signal strength P_r, is given by

$$P_r[dB] = P_t[dB] - 10 \cdot \log_{10}(4\pi/\lambda)^2 - 10 \cdot \log_{10}(d^\alpha) \qquad (1)$$

where P_t is transmit signal strength, λ is wavelength, d is distance, and α is the attenuation factor (α>=2.0). This formula states that the transmitting power, in other

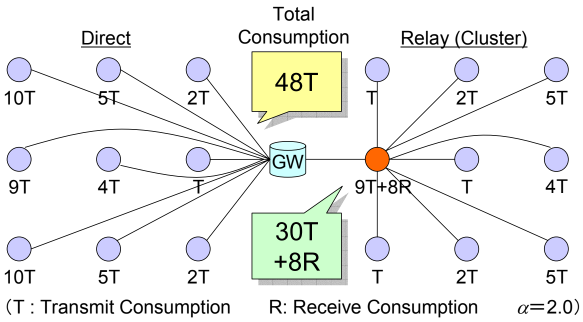


Figure 1. Direct communication and Relay communication

Table 1. Comparison of radio systems

	Specified low power radio station[3][4] (429MHz)	Low-power non-licensed transmitters[3] (300MHz)	802.11b
Transmission Range	~several 100m	～15m	~200m
Current Consumption	Tx:10~24mA Rx:16~20mA	Tx:3~20mA Rx:2~10mA	Tx:300mA Rx:200mA

words, energy consumption, that is needed to communicate increases with the distance between nodes. Therefore, there may be cases in which the total energy consumption can be reduced by replacing direct communication with multi-hop communication, see Figure 1.

2.2. Data Aggregation at Cluster Heads

Cluster heads can aggregate the data transmitted from child nodes, and then compress or fuse the data. As a result, the total amount of data transmitted from cluster heads will be relatively small. If the energy consumption needed to compress or fuse the data is low enough, total energy consumption can be reduced.

3. RADIO MODEL

3.1. First-Order Radio Model

The first-order radio model is proposed in [1], and it is based on formula (1). $E_{T\text{-}elec}$ and $E_{R\text{-}elec}$ are the transmitting or receiving energy consumption per bit, respectively. They depend on circuit factors such as digital coding system used, modulation format, and so on. ε_{amp} is the energy consumption coefficient of the amplifier. With these parameters, energy consumption at transmitter E_T and at receiver E_R can be represented by the next equations.

$$E_T(k,d) = E_{T-elec} * k + \varepsilon_{amp} * k * d^4 \qquad (2)$$
$$E_R(k) = E_{R-elec} * k$$

d is distance between nodes, and k is the amount of data transmitted and received, see Figure 2. Assuming multi path fading in a realistic environment, we use α=4.0 with $E_{T\text{-}elec}$ = $E_{R\text{-}elec}$ = 50J/bit and ε_{amp} = 0.0013pJ/bit/m^4[1].

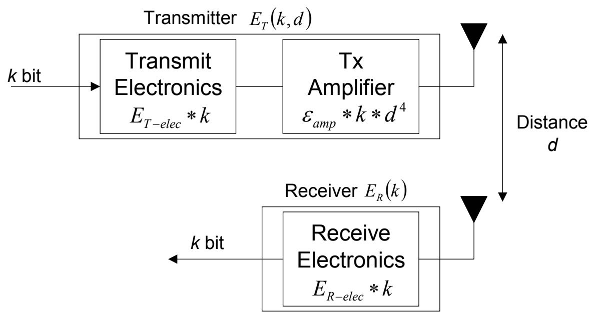


Figure 2. First-order radio model

Table 2. Current consumption/Output-power and Transmission range

	Current (mA)	Output (dBm)	Max Range (m) α=4	Max Range (m) α=3.4
Tx	10.3	-20	49.9	99.4
	12.1	-5	118.2	274.5
	13.7	0	157.7	385.1
	16.8	5	210.2	540.3
	23.4	10	280.4	758.0
Rx	17.3			

3.2. Radio Model depends Actual Device

We also consider an energy consumption model that mirrors a real device. We considered the radio device CC1020 produced by Chipcon[2]. CC1020 can control the transmit power. Its transmit/receive energy consumption is low compared to other radio devices, for example 802.11b devices (Table 1). We use parameters indicated for using CC1020 in a 400MHz bandwidth. We assume that 5 step power control can be utilized, and calculate the transmission range as per Table 2 by using formula (1) and the data sheet of CC1020. As is often the case with the first order model, we assume multi path fading and use α=4.0 (Eq. (2)). In Table 2, max transmission range when T_x is 10dBm is calculated to be about 280 meters, but this is smaller than the 700~800 meter range provided by other specified low power radio devices, for example, current transceiver sets. If α=3.4, the maximum transmission range becomes about 700~800 meter which better fits real situations, so we also consider α=3.4 as the case where the transmit power is maximum as a reference.

4. ENERGY CONSUMPTION OF OUR CLUSTER MODEL

4.1. 1-Hop Cluster Model and Network Model

We considered a network consisting of 24 nodes and one gateway (GW) in a 5x5 reticular pattern (M meters per side), see Figure 3. We put the GW at one corner of

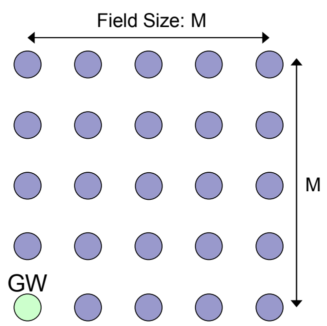
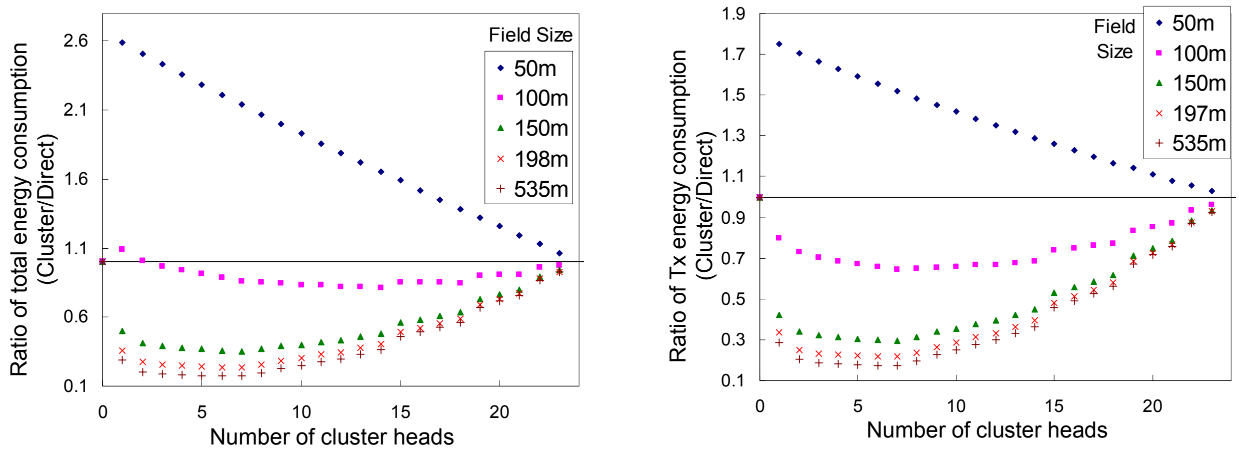


Figure 3. Deployment of nodes and GW



(a) Ratio of (Tx + Rx) consumption

(b) Ratio of Tx consumption

Figure 4. Ratio of energy consumption of Clustering to Direct Communication (First-order radio model)

the network. We set the number of cluster heads from 0 to 23; each cluster head is a regular node. Cluster heads communicate with the GW, and the other nodes communicate with the closest cluster head. If there are several cluster heads located at the same distance, the node selects the cluster head that is nearest to the GW.

4.2. Calculation Model

We calculate the total energy consumption of all nodes on the condition that all nodes can communicate with the GW directly. Therefore, when we use the CC1020 model, the maximum distance from the GW to edge nodes is about 280 (α=4.0) or 760 (α=3.4) meters. To make the comparison valid, we limit the transmission range of the first-order radio model accordingly.

Every node controls their transmission power as appropriate according to the distance to its cluster head. We don't consider the energy consumed in constructing the cluster nor the energy consumed at the GW. We also assume no interference and no collision. That is, the total energy consumption is equal to the total of the energy consumed to transmit data to and receive data at the cluster heads.

We assume every node transmits an identical unit of data to the GW, and we calculate the total energy consumption for all patterns of cluster configuration on the condition that the number of cluster heads is fixed. We then choose smallest result. The evaluation function is the ratio of total energy consumption for the cluster configuration to the total energy consumption when all nodes communicate with the GW directly.

4.3. Results of 1-Hop Cluster Model

4.3.1. Results of First-Order Radio Model

At first, we report the total energy consumption using the first-order radio model. Figure 4 shows the ratio of total energy consumption when field size changes from 50 meters to 198 meters (and 535 meters, α=3.4) the maximum field size in which the node farthest from the GW can communicate with the GW directly. This result shows that clustering can reduce the energy consumption if field size, in other words, transmission range to the GW is large enough.

4.3.2. Results of CC1020 model

I. CC1020 without Data Aggregation

In this section, we calculate the total energy consumption using the CC1020 radio model without data aggregation and fusion. Figure 5 shows the result. Regardless of the field size, clustering in this system never reduces total energy consumption. In other words, if nodes can communicate with the GW directly, direct communication is best from the viewpoint of reducing total energy consumption.

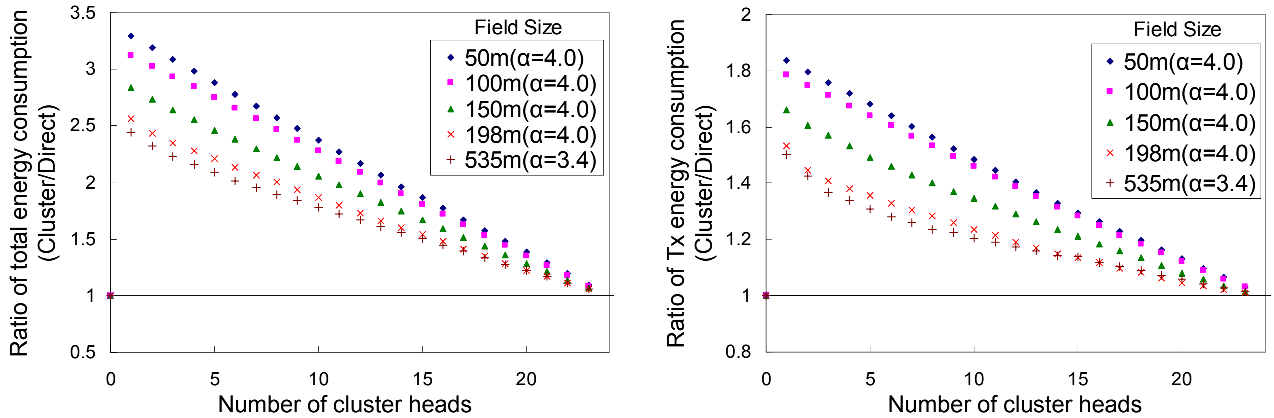
Also, Figure 5 shows that increasing the field size reduces the ratio of total energy consumption.

II. CC1020 with Data Aggregation

We calculated the total energy consumption when cluster heads performed data aggregation and fusion. We assumed that each cluster head aggregated data from all child nodes once, and fused the aggregated data into one unit which was then transmitted to the GW. We also assumed that cluster heads consumed no energy in fusing the data. Other conditions are the same as in Section I.

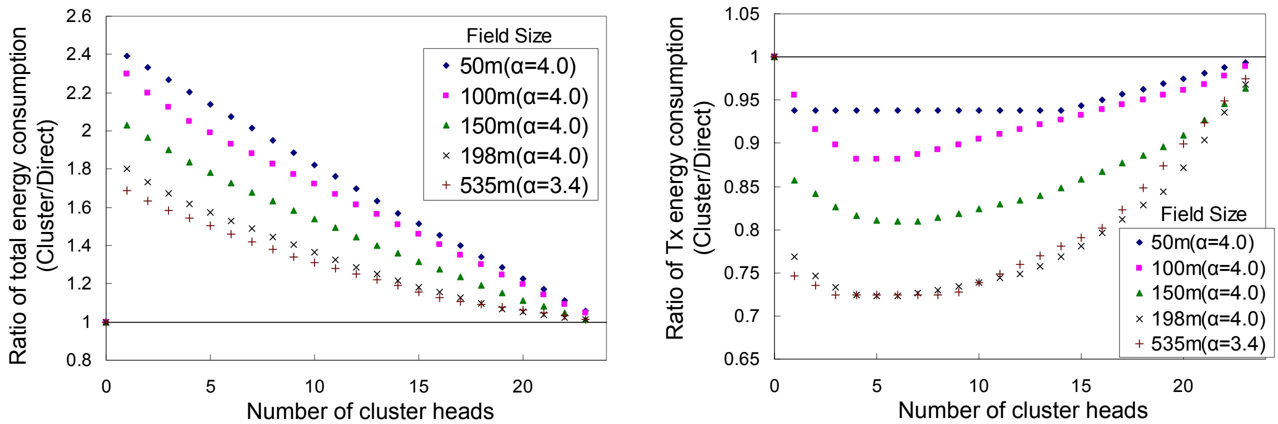
Figure 6 shows the results. Compared to Figure 5, the ratio of the total energy consumption becomes smaller, but in any case, clustering raises the total energy consumption compared to direct communication. This result shows that there is no advantage in constructing clusters using CC1020 if all nodes can communicate with the GW directly even if data aggregation and complete fusion are used.

From the results in Section I and this section, we find there is no advantage to clustering in terms of energy consumption if we use the existing radio device CC1020 in the case where all nodes can communicate



(a) Ratio of (Tx + Rx) consumption (b) Ratio of Tx consumption

Figure 5. Ratio of energy consumption of Clustering to Direct Communication (CC1020 without data fusion)



(a) Ratio of (Tx + Rx) consumption (b) Ratio of Tx consumption

Figure 6. Ratio of energy consumption of Clustering to Direct Communication (CC1020 with data fusion)

with the GW directly. If multi-hop communication is necessary to transmit data to the GW, total energy consumption might be smaller by selecting the route that minimizes the number of hops if all routes have similar total distances.

III. Modified CC1020

We consider that there are two main reasons why the total energy consumption is not reduced by clustering with data aggregation and fusion.

A) Transmitting circuit inefficiencies mean that there is little difference in transmitting a signal over long and short distances. So the savings in energy made possible by using short-range relay links is insufficient.

B) The energy consumed in receiving data is quite high, and overwhelms any savings offered by relaying data.

Figures 5(b) show the total energy consumption of just transmission. This figure shows that clustering doesn't reduce the transmit energy consumption when we use CC1020. This is because, as Figure 7 shows, CC1020 provides poor granularity (current consumption versus transmission distance) compared to that provided by formula (1) and also the first-order model (Eq. (2)). We note CC1020's granularity can be improved and its consumption reduced if we can lower the energy consumption of the oscillator and the transmitting circuit (Figure 8-A', Figure 7-A'). Therefore, there is a possibility that CC1020 clustering may reduce the total energy consumption. On the other hand, Figure 6(b) shows that energy consumption of transmission is reduced when data aggregation and fusion are performed, but the ratio of total energy consumption including receiving remains larger than 1.0, see Figure 6(a). This is because the additional receive energy consumption is larger than the reduction in transmit energy consumption.

Therefore we investigated what changes would be needed to make clustering, without data aggregation or fusion, worthwhile. There are two main tactics

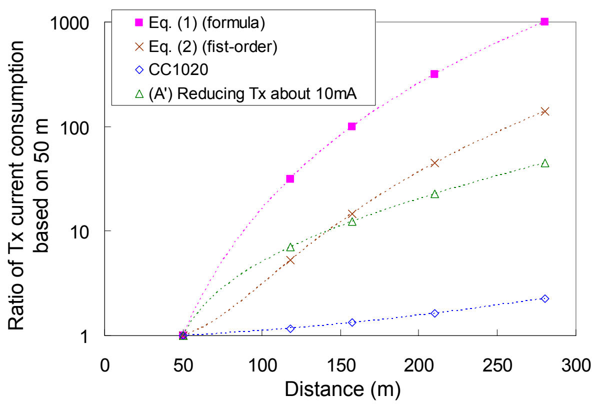


Figure 7. Comparison of current consumption

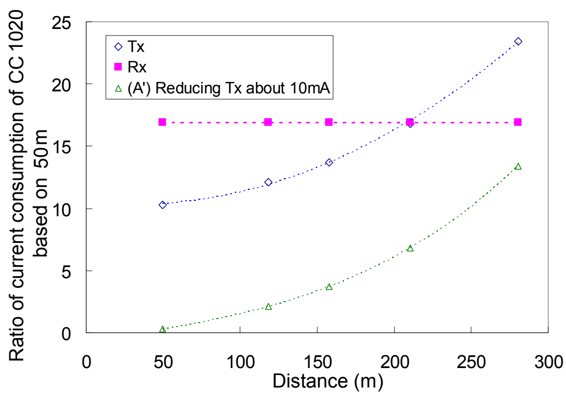


Figure 8. Current consumption of CC1020

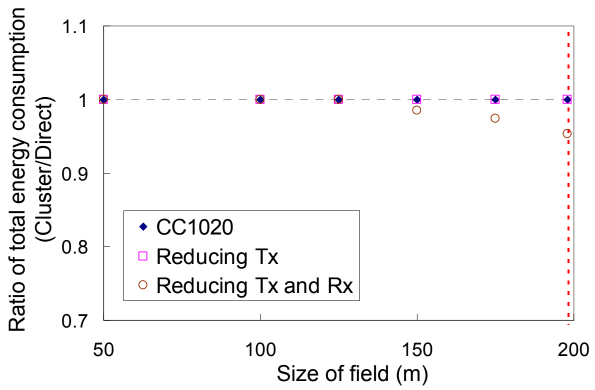


Figure 9. Smallest ratio of energy consumption after changing Tx/Rx performance of CC1020

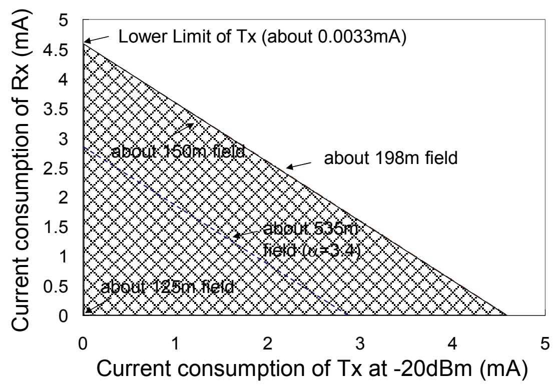


Figure 10. Reduced Tx/Rx current consumption that permits total energy consumption to be reduced by clustering

A') Reducing transmit energy consumption by optimizing the oscillator and the transmitting circuit.

B') Reducing receive energy consumption.

The results are shown in Figures 9 and 10. Figure 9 shows the ratio of total energy consumption if the transmit current consumption is reduced by about 10mA and the receive current consumption is reduced to 1.73mA (tenth the typical receive current consumption). The transmit current consumption reduced by 10mA is smallest value that can assure the necessary transmit power based on minimum value -20dBm given the typical driving voltage, 3V, of CC1020. We note that the ratio of total energy consumption is 0.99 for the field size of 535m (α=3.4, maximum size of field) but this is not depicted in Figure 9.

Figure 10 shows the patterns of transmit/receive current consumption given the enough transmit power of -20dBm (i.e. about 50m). The dashed line shows the maximum combination of transmit/receive current consumption that can still reduce the total energy consumption for each field size. Shaded regions indicate combinations that enable reduction in total energy consumption. From these results, we find that clustering can offer lower total energy consumption than direct communication if CC1020 performance is enhanced. However, the advantage is relatively small.

Total energy consumption will be improved if the radio section provides a more formula-like current consumption characteristic. This is possible by, for example, creating an amplifier that makes the power consumption of the transmission circuit more closely follow changes in the transmission distance. Considering the minimum power needed to power the radio section (current technologies), however, these changes are not feasible or not practical in low out-put and low energy consumption devices. Consequently, in a multi-hop network constructed by low power devices such as CC1020, it is inefficient to make clusters aggressively within the direct transmission range. On the other hand, in the case where high-output radio devices are deployed, the power consumption needed to make and transmit radio wave will be small compared to the changes in transmission energy consumption (that is, energy consumption model becomes similar to the formula), which suggests that clustering and data relay/fusion might reduce the total energy consumption. This is expected from Figures 5, 6. In these figures, the larger the size of the field becomes (that is, the larger the transmitting distance becomes), the smaller the ratio of total energy consumption becomes.

5. Conclusion

We determined whether clustering was a valid approach to reducing the total energy consumption of wireless sensor networks if all nodes can communicate with the GW directly. We used a first-order radio model and the parameters of an existing radio device, CC1020, to calculate energy consumption. From the results, we find that, with first-order radio model of the parameters for high performance wireless system, e.g. Bluetooth, multi-hop communication (that is, clustering) is better than direct communication to the gateway (GW) if the size of the field is large enough. And with CC1020, direct communication to the GW is better than multi-hop communication.

Consequently, we must consider the performance of the radio device used and the size of the field of the network to judge whether clustering is effective or not.

References

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