Analysis of Energy Consumption for a Biological Clustering Method in Sensor Networks

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Abstract

In this paper we present an analytical model for performance evaluation of a clustered sensor network. We examine the energy required for a single round of clustering for a biologically-inspired extension of the well-known LEACH clustering method. We use methods from stochastic geometry to model the locations of the node clusters using a hard-core Matérn cluster process. Based on the computation of the energy consumption of the whole clustering procedure we determine the most energy-efficient setting of the cluster radius. Furthermore, we consider the efficiency of clustering when the sensed data can be compressed at the cluster heads.

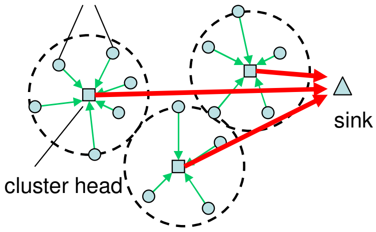
1. Introduction

With the recent developments in Micro Electro Mechanical System (MEMS) technology, large-scale networks of integrated wireless sensor nodes have become available [1]. By deploying networks of sensors, information about behavior, conditions, and positions of entities in an environment are gathered and forwarded to a sink for further processing. The nodes are equipped with a sensing device, radio transmitter, and are usually battery operated. Since they are designed to operate autonomously, they must be able to set up a communication network in an ad-hoc manner and be able to adapt to changes in the network topology, when individual nodes may fail due to exhausted energy resources. Conservation of energy is, thus, a key issue in the deployment of sensor networks. Most energy is consumed by the communication over the radio link [20].

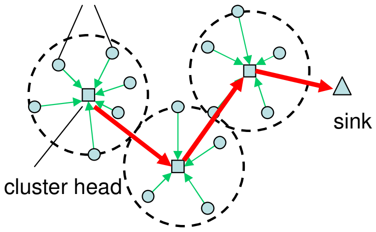
Recently, several publications have shown the benefits of using clustering methods in order to save energy and prolong the lifetime of the network, e.g. [7, 10, 12]. In clustered sensor networks, the sensor nodes do not transmit their collected data to the sink, but to designated cluster heads which aggregate the data packets and send them directly or via multi-hop communication to the sink. Thus, choosing the appropriate sizes and number of clusters is essential for the performance of the network lifetime. If the cluster's radius is too large, it will host many nodes and a lot of energy is wasted due to inter-cluster collisions. On the other hand, if the radius is too small, a large number of clusters is required to cover the observation area and many of them will have to transmit their data over a large distance to the sink.

In the model of the biologically inspired clustering approach given in [12], the cluster radius is an input parameter which we intend to optimize in this paper. We model the locations of the sensor nodes to be following a spatial Poisson process, which is a well known approach from stochastic geometry [13]. Since the clusters are formed using random variables, the cluster process can be described by a hard-core Matérn process. This mathematical description permits a characterization of the density of the cluster process. Whereas in other work the mathematical evaluation of the energy dissipation is often only performed for the data transmission phase after the clusters have been formed [9], we give the total energy required for a single round of clustering in this paper. This includes the energy needed for each phase of cluster set-up, as well as the actual data transmission phase using a TDMA schedule. Although our focus is on the clustering approach in [12], the basic model can be easily modified to be used with different radio models and energy dissipation models.

The paper is organized as follows. In Section 2, we describe the basic properties of clustering in sensor networks and briefly review the clustering algorithm from [12]. This is followed in Section 3 by the analytical model for the energy consumption in a single round. Numerical results on evaluating the energy efficient parameters are provided in Section 4 and the paper is concluded in Section 5 with an outlook on future work.



(a) 2-hop transmission



(b) multi-hop transmission

Figure 1: Clustered sensor networks

2. Clustering in Sensor Networks

In order to simplify the electronic circuitry of the sensor nodes, they only collect the sensor information and forward the data to the sink where the processing is done. If all nodes transmit directly to the sink, the system would not be scalable as the many-to-one transmission can consist of hundreds or thousands of nodes [6]. Therefore, clustering methods have been proposed, in which the nodes within a cluster send the data to a designated node, called *cluster head*. It collects the data locally from the other cluster members and transmits the aggregated data either directly or via multi-hop transmission to the sink, see Fig. 1. Furthermore, if the data packets are locally correlated, they can be compressed and fused to shorter data messages at the cluster heads for more efficient transmission [8, 14]. Since the cluster heads spend more energy than the other cluster members, their role is rotated among all nodes in order to equalize energy consumption. Recently a large number of proposals for energy-efficient clustering techniques have been published, e.g. [3, 4, 18]. The problem of assigning the clusters is closely related to the routing strategy in which way the data is forwarded from cluster heads to the sink.

One of the most well-known clustering approaches is the Low Energy Adaptive Clustering Hierarchy (LEACH) [10] method since many other methods are derived from it. In LEACH, a predetermined percentage of sensor nodes become cluster heads which advertise their candidacy to the other nodes. Hearing these advertisement messages, each sensor node chooses the nearest cluster head and registers itself as a cluster member leading to the formation of clusters. Cluster members send their sensor data to the cluster head which combines all received data into a single data message that is sent to the remote base station. Since a cluster head expends more energy than its members in advertising and receiving, fusing, and emitting data to a base station, its role is rotated among all nodes.

Based on LEACH, several other clustering approaches have been proposed in the literature improving its performance, e.g. [2], LEACH-C [9], HEED [21], PEGASIS [17]. In this work we focus on another such extension which was presented in [12] and forms the clusters based on ANTCLUST [15]. ANTCLUST is a model of an ant colonial closure to solve clustering problems. Ants recognize each other by exchanging chemical substances. Based on the similarity of these substances, clusters are created, merged, or deleted. In the ANTCLUST-based clustering method, sensor nodes with more residual energy become cluster heads independently. Then, randomly chosen nodes meet with each other and clusters are created, merged, and discarded through local meetings. Each sensor node with less residual energy chooses a cluster based on the residual energy of the cluster head, its distance to the cluster head, and an estimation of the cluster size. Eventually energy-efficient clusters are formed that result in an extension of the lifetime of a sensor network.

3. Analysis of Energy Consumption

In the following we will present the model for energy consumption for the clustering method of [12]. We assume that the nodes are randomly located in the square $W \times W$ observation window by following a spatial homogeneous Poisson process [13] with density λ corresponding to the average number of nodes per unit area size. So the average total number of nodes is then given as N_w.

$$N_w = \lambda W^2 \tag{1}$$

An example snapshot of a homogeneous spatial Poisson process is shown in Fig. 2.

In Section 3.1 we describe the energy for transmitting and receiving data for a single node and extend this to the communication for a single cluster in Section 3.2. Finally, in Section 3.3 the total energy due to clustering in the whole network is derived.

3.1. Basic Energy Consumption Model

We adopt the energy consumption model given in [9] for transmitting and receiving data with length l bits when x is

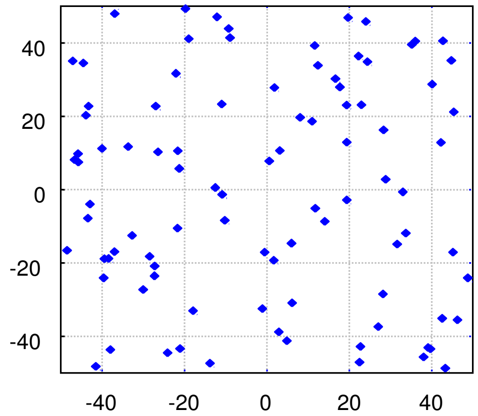


Figure 2: Snapshot of Poisson process

the distance between transmitter and receiver.

$$E_{Tx}(l,d) = \begin{cases} l\left(E_{elec} + \varepsilon_{fs}\, x^2\right) & x < d_0 \\ l\left(E_{elec} + \varepsilon_{mp}\, x^4\right) & x \geq d_0 \end{cases} \quad (2)$$

$$E_{Rx}(l) = l\, E_{elec} \quad (3)$$

The electronics energy E_{elec} is 50 nJ/bit and $\varepsilon_{fs} = 10$ pJ/bit/m^2 is the energy for the transmitter amplification in free space. The corresponding value for the multi-path fading model is chosen as 0.0013 pJ/bit/m^4. For transmission over a distance less than $d_0 = 75$ m will use the free space model and greater than d_0 the multi-path fading model. Aggregating data messages consumes $E_{fuse} = 5$ nJ/bit/signal per bit.

3.2. Energy Consumption per Cluster

Let us consider a single cluster with radius R. Due to the properties of the Poisson process, the average number of nodes in the cluster with radius R can be given by

$$N_n = \lambda \pi R^2. \quad (4)$$

We now consider the energy consumption for all nodes transmitting their gathered data of length l to the cluster head in a single cluster. Let us assume that collisions do not occur. The average energy from transmissions of all nodes in the cluster with radius R can be formulated immediately by Campbell's Theorem [13]. We have in particular the following theorem.

Theorem 1 *Let $\Pi = \{x_1, x_2, \ldots\}$ be a Poisson process with density λ, and let $f : \mathbb{R}^2 \to \mathbb{R}$ be a measurable function. Let S_A be the following sum*

$$S_A = \sum_{x_i \in A \cap \Pi} f(x_i), \quad (5)$$

defined for any compact set A, then

$$E[S_A] = \int_A f(x)\, \lambda\, dx. \quad (6)$$

In our case, $f(x)$ is the energy used by a node located at x to transmit to the cluster head. Thus, the total transmitter energy is given by E_c in Eqn. (7).

$$\begin{aligned} E_c(l,R) &= \int_0^{2\pi} d\theta \int_0^R 2z\, dz \lambda \left[l E_{elec} + l\, \varepsilon_{fs} z^2\right] \\ &= N_n\, E_{Tx}(l,R) \end{aligned} \quad (7)$$

3.3. Energy Consumption of the Clustering Method

In this section we will study the energy consumption from the 2-hop model as described in [12]. The cluster radius R is a parameter of the algorithm and our goal is to find an energy-optimal value of R.

The clustering method itself is performed in rounds. In each round there will be a loss of energy that we wish to estimate in this section. As described in [12], each round consists of four steps:

1. cluster head candidacy phase,
2. cluster formation phase,
3. registration phase, and
4. transmission phase.

An overview of the clustering phases is shown in Fig. 3 and a more detailed description of the algorithm can be found in [12].

In the following we will characterize the energy consumed in each of these phases individually.

3.3.1. Cluster Head Candidacy Phase. In this phase, tentative clusters are formed. Each cluster head considers itself at the beginning to be a candidate for a cluster head. It advertises itself by a broadcast transmission at a random time $\tau_i = T(1 - P_i)$ depending on its residual energy and the random variable P_i. Let us assume that all nodes have the same residual energy when competing for cluster head candidacy. This assumption is necessary in order to make the problem mathematically tractable. Then, each node has the equal probability to act as cluster head and the random variables τ_i are thus independent and uniformly distributed in interval $[0, T]$. All points are thus marked with the value of the random variable τ_i and a node i at location x is called cluster head, if within a circle of radius R and center x_i, there is no point whose mark is smaller than τ_i. This is the definition of the Matérn hard-core process. As stated in

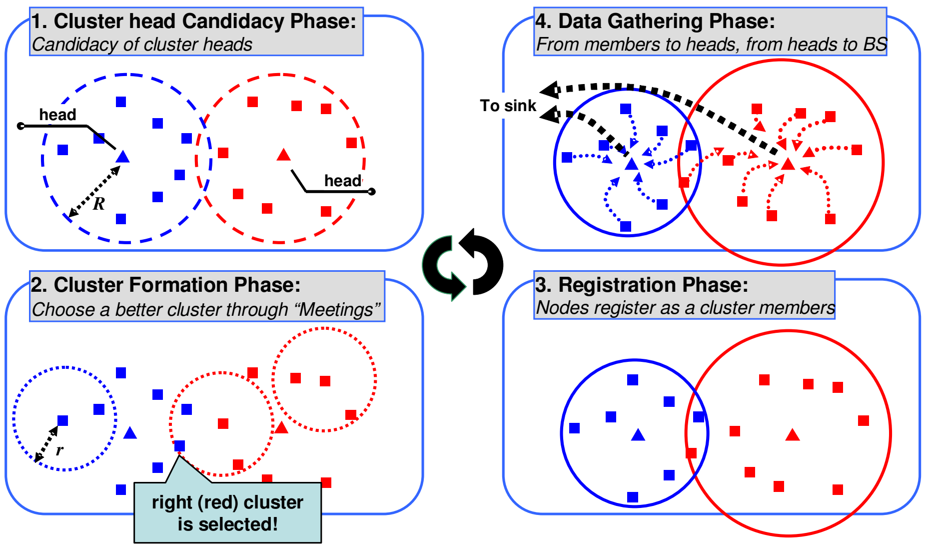


Figure 3: Overview of the clustering phases

[19], section 5.4, a Matérn hard-core process is essentially a dependent thinning applied to a Poisson process. Lazily speaking, the thinning consists in retaining a point with a mark that is the greatest compared to the mark of points lying in a circle centered at this kept point.

The point process obtained from this dependent thinning of the original Poisson process is stationary and its intensity is equal to

$$\lambda_c = \frac{1 - \exp(-\lambda \pi R^2)}{\pi R^2}. \tag{8}$$

The average number of clusters can then be given as

$$N_c = \lambda_c W^2. \tag{9}$$

Let l_B denote the length of the broadcast message in bits and R is the advertisement radius. We have on average N_c clusters in the observation windows. Therefore, N_c nodes will have successful cluster head advertisement broadcasts on average. Additionally, in average N_n nodes acknowledge the broadcast in each cluster, which gives the energy E_1 for the first phase.

$$E_1 = N_c \left[E_{Tx}(l_B, R) + N_n E_{Rx}(l_B)\right] \tag{10}$$

3.3.2. Cluster Formation Phase. In the cluster formation phase, a percentage P_{ex} of the total nodes perform local meetings, i.e, they broadcast the information about themselves and their cluster within a smaller reception radius r. All nodes receiving this signal update their cluster membership based on this new information.

$$E_2 = N_w P_{ex} \left[E_{Tx}(l_B, r) + \lambda \pi r^2 E_{Rx}(l_B)\right] \tag{11}$$

3.3.3. Registration Phase. In the registration phase, each node in the cluster registers itself at the cluster head with a message of length l_R and the cluster head broadcasts as response the TDMA schedule of length $l_S = 16 + 8\,N_n$.

$$\begin{aligned} E_3 = N_c \big[& E_c(l_R, R) + N_n E_{Rx}(l_R) \\ & + E_{Tx}(l_S, R) + N_n E_{Rx}(l_S)\big] \end{aligned} \tag{12}$$

3.3.4. Data Transmission Phase. The data transmission phase can be split up in two parts: (*i*) the communication of the cluster members, and (*ii*) the communication of the cluster heads. The first part describes the transmission of the messages from the cluster members to their cluster heads and can be expressed simply by $E_c(l_M, R)$, where l_M is the message length of the sensed data.

For the computation of the second part, we must apply the following considerations. Each cluster head receives the messages with length l_M from all of the nodes in the cluster, merges the received data and its own data to a single message of length $\tilde{l}_M$ and transmits it to the base station. Additionally, we must consider the energy that is required for the transmission of the data from the cluster head to the base station. The BS is located at the coordinates $(bx, by) \in \mathbb{R}^2$, somewhere within or outside the observation window. The distance to an arbitrary node with the coordinates (x, y) is given by

$$d_{BS}(\{x, y\}) = \sqrt{(bx - x)^2 + (by - y)^2}.$$

Since the node process is stationary, Campbell's theorem in its general expression (see [5], section 12.1) can be used. The mean energy required for the transmission of the data from all cluster heads to the BS is given by

$$E_h = \lambda_c \int_0^W \int_0^W E_{Tx}(\tilde{l}_M, d_{BS}(\{x,y\}))\, dx\, dy \quad (13)$$

where we denote $\tilde{l}_M$ as the length of the aggregated message at the cluster head, which it transmits to the BS.

Thus, the total energy consumed for the communication during the fourth round is then given as

$$\begin{aligned} E_4 = N_c\big[E_c(l_M, R) + N_n\, E_{Rx}(l_M) \\ + (N_n+1)\, l_M\, E_{fuse}\big] + E_h \end{aligned} \quad (14)$$

Finally, the total energy consumption per round is the sum of the energy consumption of all four phases.

$$E_{total} = \sum_{i=1}^{4} E_i \quad (15)$$

3.4. Model of Message Aggregation

Since all data is locally collected from the cluster at the cluster heads, there is a potential benefit of compressing the data messages into a packet of smaller size before transmitting it to the BS. Since the compressibility of the data depends highly on the type of application data we are transmitting, we need to give a generic description of the size reduction. Let us assume that a cluster consists of N_n nodes and each transmits a data message of length l_M to the cluster head. The cluster head receives these messages and fuses it together with its own measured data to a single packet. We can therefore assume that the new packet size will be somewhere between l_M (when perfect compression is possible) up to $N_n\, l_M$ (for no compression). In order to parameterize the compression we introduce the (linear) *compression factor* $\rho \in [0,1]$ as given in (16).

$$\tilde{l}_M = [N - (N-1)\,\rho]\; l_M \quad (16)$$

Note that we do not consider the energy used for fusing the data at the base station, as we assume that it has unlimited power and is not relevant for our study.

4. Evaluation of the Clustering Parameters

Let us now give some numerical results and compare both clustering methods for their energy efficiency. The parameters we consider for the message lengths are given in Tab. 1 and correspond to those found in [12]. Furthermore, the desired percentage of cluster heads P_{ex} is chosen as 0.3.

We consider the layout of the observation area and the BS as described in [10]. In this scenario, the BS is located outside the window at position at $bx = \frac{W}{2}$, $by = W + \Delta y$, with $\Delta y > d_0$ as shown in Fig. 4. This requires that the second equation of (2) is used for all transmissions from the cluster heads to the BS. The considered layout is shown in Fig. 4.

Table 1: Message length parameters

variable	length [bit]
l_M	2000
l_B	60
l_R	16
l_S	$16 + 8\,N_n$

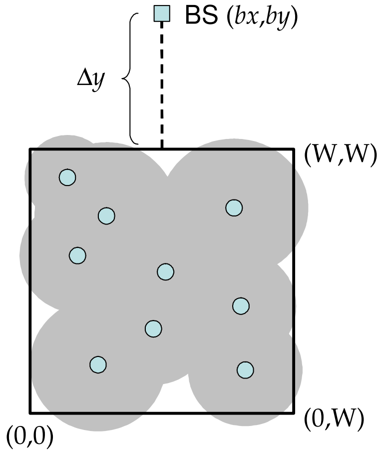


Figure 4: Considered BS layout

If we insert the values for bx and by into Eqn. (13), we obtain the following result.

$$E_h = \lambda_c\, \tilde{l}_M\, W^2\, [E_{elec} + \varepsilon_{mp}\, \alpha] \quad (17)$$

where α is a constant defined as

$$\begin{aligned} \alpha = \Delta y^4 + 2\Delta y^3 W + \frac{13}{6}\,\Delta y^2 W^2 \\ + \frac{7}{6}\Delta y W^3 + \frac{193}{720}\, W^4. \end{aligned} \quad (18)$$

4.1. Energy for Direct Transmissions

In order to evaluate the benefits in energy consumption of the clustering scheme we need to compare its performance with that of non-clustering. We do not investigate the effects of CSMA/CA MAC collisions at this point, but it should be remarked that the MAC protocol does not scale well with the number of nodes due to the small backoff window sizes. In this study, we entirely focus on the energy consumption. When we assume that all nodes (even those very remote) are able to reach the BS with a direct transmission, the whole overhead from generating the clusters is not required. We wish to examine at what node densities

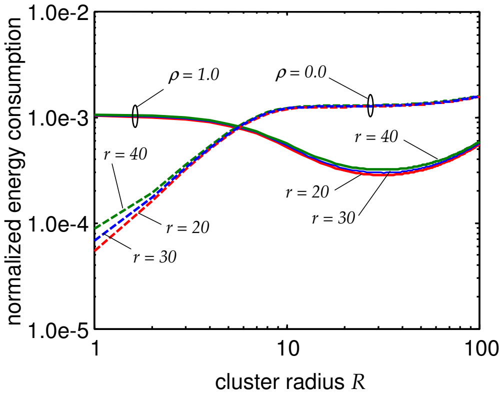


Figure 5: Energy consumption over cluster radius R

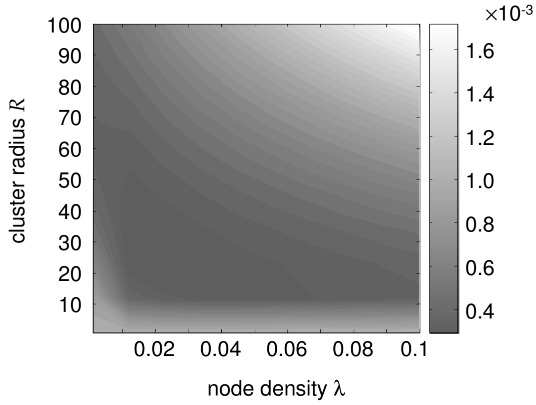


Figure 6: Energy consumption over cluster radius R and density λ

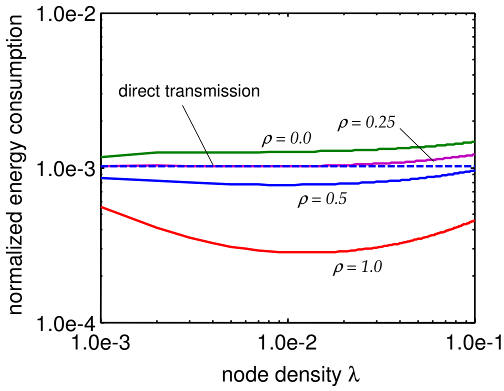


Figure 7: Comparison between clustering and direct transmission

and windows sizes it is better to use our clustering method rather than direct transmissions.

The total energy with direct transmission is then similar to the term given in (17) for the transmission in the fourth phase and the reception of these signals.

$$\hat{E}_{total} = \lambda\, l_M\, W^2\, \left[2\, E_{elec} + \varepsilon_{mp}\, \alpha\right] \tag{19}$$

The term α corresponds to the one defined in (18).

4.2. Optimal Cluster Radius

The normalized energy consumption is depicted as a function of the cluster radius R in Fig. 5. Here, we normalized the total energy E_{total} by the total number of nodes to obtain the average energy consumption per node. We used a node density of $\lambda = 0.01$ and a window size of $W = 100$ to obtain on average 100 nodes in total. The two extreme compression settings of $\rho = 0.0$ and $\rho = 1.0$ were used. We can see the following results. For $\rho = 1.0$ (perfect compression), there exists a global minimal radius which is the most energy efficient setting at about $R^* = 32$. On the other hand, when we have no compression ($\rho = 0.0$), this means that there is no real benefit obtained from clustering, since the energy consumption is simply shifted from the cluster members to the cluster heads. This result is illustrated by the global minimum being for $R \to 0$. In both cases, however, we can recognize that the influence of the meeting radius r is hardly visible. In the following, we will therefore choose it at $r = 20$ and $\rho = 0.5$ for our further experiments.

The influence of both parameters, cluster radius R and node density λ, is illustrated in Fig. 6. The origin of this graph lies in the lower left corner. We can recognize that there is an optimal region with the darkest color where the energy is lowest and that corresponds to the area of the minimum found in Fig. 5. Too small or too large cluster radii cause higher energy consumption and when the density λ reduces to zero, the benefits from clustering also disappear as the distance between nodes gets too large.

4.3. Evaluation of Compression

Let us now compare the clustering method with the case of direct transmissions. The energy consumed per node is plotted in Fig. 7 for both cases with and without clustering. Obviously, the average energy per node in the direct transmission case is independent of the node density, as there is no interaction among the nodes. When we have clustering, it depends on the compression factor, if we can achieve a better performance than direct transmissions. For high compression ratio, we can recognize in Fig. 7 that clustering is beneficial from energy viewpoint, whereas when there is no compression ($\rho = 0$) the overhead of generating the clusters prevails. In general, we can say that when the compression ratio is less than 0.25 direct transmission requires less energy than our clustering method. Another interesting feature we can recognize from Fig. 7 is that for $\rho > 0.25$ exists an optimal node density λ where we have

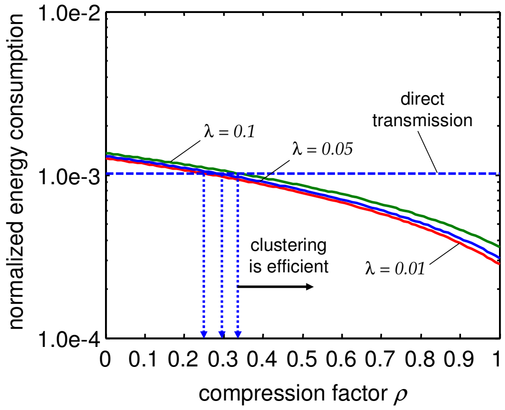


Figure 8: Efficiency of clustering in terms of compression

the lowest energy consumption per node.

Fig. 8 shows this issue in more detail. In this figure, we plotted the compression factor ρ on the x-axis and the energy per node on the y-axis. This figure illustrates the efficiency of clustering in terms of the compression factor ρ. The points at which the curves for direct transmission and clustering intersect, show us from which compression ratios on it is better to perform clustering. For smaller ρ, direct transmission is better in energy efficiency. Another advantage not shown in this figure is that clustering reduces the number of collisions in the channel as less nodes compete simultaneously for access.

5. Conclusion

In this paper we presented a mathematical model for calculating the average energy consumption in a sensor network operating with the biologically-inspired clustering method from [12]. We modeled the node distribution with a spatial point process to take the randomness of their locations into account and obtained an analytical value for the energy consumption of a sensor network.

We could see that an energy-optimal cluster radius exists and that the compression ratio and node density lead to a tradeoff point, where direct transmission without the overhead of clustering appears to be more energy-efficient. This comparison is, however, only hypothetical, as the direct transmission method performs in reality much worse due to collisions on the MAC layer.

Although we focused on a specific clustering method, this type of analysis is applicable to any other clustering approach as well. With this analysis, we are able to obtain the optimal parameter settings for the clustering methods, when the area size, node density, and compressibility of the data messages is known. These are typically application specific values.

In the future, we wish to extend this model with spatial node distributions to the case where the data from the cluster heads to the BS is no longer transmitted directly, but via multi-hop transmission over other cluster heads. Furthermore, enhancing these energy consumption equations with a more detailed model of the retransmissions on the MAC layer is the subject of further research. This seems especially important as the considered clustering approaches often make the unrealistic assumption that several different MAC protocols can be used. Recently, the ZigBee [22] specification using the IEEE 802.15.4 [11] MAC protocol has received growing attention. We wish to include a model for the energy dissipated due to the CSMA/CA MAC protocol for IEEE 802.15.4, e.g. [16], in the mathematical framework proposed in this paper.

Acknowledgments

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