Energy Efficient Data Collection in Sensor Networks

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Abstract — **We consider the problem of data collection from sensor networks using multiple access points. These access points could be intelligent and powerful sensors acting as cluster heads or just fixed collecting stations covering the network. The coverage areas of the access points may overlap, making transmissions from overlapping areas more energy efficient.**

With energy efficiency as the metric, we study cross-layer strategies where a fraction of the data is routed across regions to areas covered by multiple access points and the remaining are directly transmitted to the APs. Using ALOHA as the random access protocol, we show that for any given routing protocol, the optimal energy efficient strategy undergoes a phase transition with respect to net traffic load: at low traffic load, the most energy efficient strategy is to route all packets to the overlapping region, whereas, at high traffic load, routing does not reduce energy consumption. Furthermore. the phase transition point is shown to be independent of the fraction of overlap.

I. Introduction

Energy efficiency is crucial to wireless sensor networks. Sensors are battery-run devices that have limited data processing and transmission capabilities. It is therefore imperative that they are operated in a manner that conserves battery energy and ensures network longevity. During the operation of a sensor network, it will be necessary to frequently collect the information that has been stored in the sensors after having sensed the field. Depending on the phenomenon sensed, the data collection rates may vary. For example, in the case of detection of a toxic chemical in a field, the information must be collected as quickly as possible. Whereas, while sensing weather conditions such as temperature and humidity, it is enough to collect the data over long periods of time.

The process of data collection may be divided into two phases. The first phase is the aggregation of information from several sensors in the field. Then, a central unit combines these individual packets appropriately to reconstruct the global information. For the first phase, the aggregation of data can occur at powerful access points (APs) in a two tier network architecture (see Figure 1), or at cluster heads in hierarchical networks. The APs can be fixed (similar to cellular base stations) or mobile [1, 8]. In hierarchical networks, the sensors are grouped into geographic clusters [2, 3] and one sensor in each cluster is designated as a clusterhead. The clusterheads or APs may then transfer their aggregated data to a central processing unit for information retrieval. In this paper, our analysis is restricted to these types of architectures.

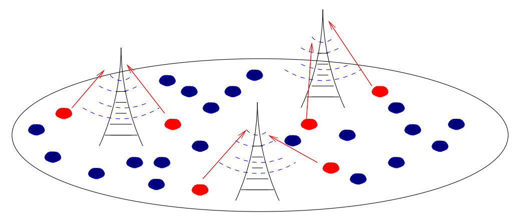

Figure 1: Sensor Networks with Multiple Access Points

In [9], we had analyzed sensor networks with a single AP with respect to optimized medium access and coding. Presence of multiple access points adds a new dimensionality to the problem, when coverage areas of APs overlap with one another. Sensors in overlapping regions have an additional diversity gain, but cause intereference at multiple receivers. More specifically, consider a simple two AP network as shown in Figure 2. Sensors in non-overlapping regions A_1, A_2 are heard by only one AP, whereas sensors in A_{12} can be heard by both APs. By suitably scheduling transmissions from different regions of the network, it is possible to optimize the required performance metric. In [15], we had theoretically analyzed the data collection problem from a purely random access perspective. We had optimized network configurations for an ALOHA medium access using throughput and efficiency as performance metrics. We showed that, transmitting only from non-overlapping regions achieves maximum throughput, whereas transmitting solely from overlapping region is energy efficient. Those results, however, are most applicable when APs are mobile, and hence, data could be gathered from all parts of the network using the mobility of APs. When access points are fixed, or when sensors communicate to stationary clusterheads, it is necessary that data is aggregated from the entire network. In this work, we utilize the analytical approach in [15], and obtain energy-efficient strategies under the fixed AP architecture.

Traditional approaches to the data collection problem involve purely multiple access schemes (eg. [4, 9, 10]) or multihop routing schemes (eg. [5, 6]). Since sensors are energy constrained and deployed in large numbers, the medium access control needs to be simple and distributed. The disadvantage of using purely random access schemes is that they are not very energy efficient especially for high throughputs. More-

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over, in networks where the data is collected by multiple APs, transmissions from a region common to multiple APs may be more energy efficient than those from a region activated by a single AP. Therefore, when APs are fixed, it may be useful to route some of the data to regions that have higher efficiency of transmission. Routing, however, requires considerable overhead and is subject to frequent updation due to random duty cycle of sensors. If these strategies are appropriately combined, it is possible to minimize the total energy.

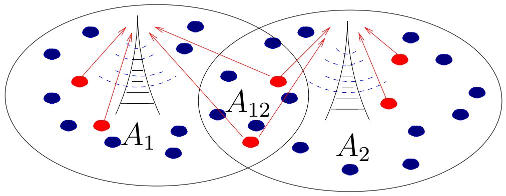

Figure 2: Example of two APs with overlapping activated region

We approach the data collection problem from such a cross layer perspective by considering strategies that involve both routing and multiple access. We establish an analytical framework that combines the MAC and routing layers. The assumption is that data is uniformly distributed across the network, and needs to be collected at a rate of λ packets per second. The collection rate could be due to the actual data generation rate at the sensors, or could be a requirement of the collecting agent (as in the case of immediate target tracking, toxin detection). We consider a general set of cross-layer strategies, where a fraction of data (α) is routed across regions (from non-overlapping to overlapping or vice-versa), and the redistributed data is transmitted to the AP using ALOHA. Our motivation for choosing ALOHA is that it is a distributed random access protocol and easy to implement, thereby appropriate for large scale sensor networks, . Furthermore, under some channel conditions, ALOHA is shown to be optimal when multipacket reception is used [11].

I.A Main Results and Organization

We consider a specific routing protocol, and characterize and evaluate the net energy (routing and AP transmission) required to sustain a given throughput. These energies are compared for different strategies, depending on the fraction α of data routed. We then optimize α for different network configurations (fraction of overlap) and different throughputs. For any routing protocol employed, we show that the optimal α undergoes a phase transition w.r.t throughput. For low throughputs, the optimal strategy is to route all packets to the overlapping region, whereas for higher throughputs, it is most efficient when no data is routed. The phase transition point is dependent on the routing protocol, but independent of the network configuration.

The paper is organized as follows. In section II, we discuss the theoretical framework for multiple access in sensor networks with multiple access points. In section III, we describe the system setup of the cross-layer design problem addressed in this paper. We then characterize the energy consumption of individual schemes in section B. Using these expressions, we derive optimal strategies in section C. Finally, conclusions and further ramifications are presented in section IV.

II. Theoretical Foundations

In this section, we discuss theoretical results which form the basis for the sensor-AP transmission model. We consider the performance of sensor networks with multiple APs under the metrics of throughput and efficiency. A simple two AP network is shown in Figure 2. Sensors are assumed to be distributed according to a Poisson model. The number of active sensors in an area A is assumed to have the probability mass function

$$\Pr(k \text{ sensors in } A) = \frac{e^{-\mu A}(\mu A)^k}{k!}. \tag{1}$$

The randomness arises due to the deployment of sensors and their random duty cycles. The motivation behind the Poisson assumption is that the distribution of sensors in non-overlapping regions are independent.

The network operates in half duplex mode. At the beginning of every slot, the APs transmit synchronous beacons. Each sensor in the activated region (A_1, A_{12}, A_2) hears the beacon(s), and transmits with some probability p which is a function of number of beacons it can hear.

II.A Physical Layer

We assume a Rayleigh fading channel. The channel gain $\gamma_{i,j,t}$ between sensor i and AP j in slot t is given by

$$\gamma_{i,j,t} = \frac{|R_{i,j,t}|^2}{h^2}, \tag{2}$$

where $R_{i,j,t}$ is a complex Gaussian random variable. The channel gain is assumed to be *i.i.d* across sensors, slots and APs. We assume that the path loss is identical for all sensors and hence is only a scaling factor. When the APs are located at a height significantly larger than the radius of activation, or if the area of each cluster is small, this channel model is sufficient. For other situations, our results would serve as useful upper bounds on performance.

We assume, all sensors transmit with finite equal power P_T. The reception at a single AP is modeled using the SINR threshold model [12]. A packet from a sensor is received successfully if the SINR is greater than a threshold β. In other words, sensor i is successful if

$$\frac{P_T \gamma_i}{\sigma^2 + \sum_{j \neq i} P_T \gamma_j} > \beta. \tag{3}$$

II.B MAC : Throughput and Efficiency

We consider two metrics for comparison of network configurations, throughput and efficiency. The throughput is defined as the average number of packets successfully received per slot. It is a measure of network latency and is a useful metric, when the objective is to collect data from the network quickly. For a network with a single AP, the throughput can be given by

$$\lambda = \mathbb{E}_n \sum_{k=1}^{n} \binom{n}{k} \frac{p^k(1-p)^{n-k}}{k!} k P_k, \tag{4}$$

where p is the transmission probability, and P_k is the probability of successful reception of a particular sensor when k sensors chose to transmit. The expectation is taken over the size of the network n. Note that P_k models the capture probabilities [13] and allows multi-packet reception. The expectation is over n, the size of the network, which, in our analysis, is Poisson distributed.

Efficency is defined as the average number of packets successfully received per transmission. It can be viewed as a measure of energy efficiency and is considered appropriate for maximizing the network lifetime. For a fixed size network, we can write the efficiency as

$$\eta = \frac{\mathbb{E}_n \sum_{k=1}^{n} \binom{n}{k} \frac{p^k (1-p)^{n-k}}{k!} k P_k}{\mathbb{E}_n np}. \quad (5)$$

In [15], we characterized the optimal configurations for maximizing throughput and efficiency individually. For maximum throughput, the optimal strategy was to activate completely non-overlapping regions, whereas, to maximize efficiency, the activation regions should overlap completely. When the access points and coverage radii are fixed, it may not be possible to activate completely overlapping or non-overlapping areas to cover the field. Therefore, it is necessary to characterize the performance of partially overlapped networks. The following theorem (from [15]) gives the throughput and optimal transmission probabilities for networks with fixed overlap ρ.

Theorem 1 *For a network with fraction of overlap* $0 < \rho < 1$*, let* p_1, p_2 *represent the transmission probabilities in the non-overlapping and overlapping regions respectively, and* $\lambda_\rho(p_1, p_2)$ *represent the throughput of the network.*
When beacons are distinguishable by sensors,
i. if $(1-\rho)\mu \geq \frac{1+\beta}{\beta}$*, then*

$$\max_{p_1, p_2} \lambda_\rho(p_1, p_2) = \max_{p_1} \lambda_\rho(p_1, 0) = 2e^{-\beta\sigma^2} \frac{1+\beta}{\beta e}.$$

ii. if $(1-\rho)\mu \leq \frac{1+\beta}{\beta}$*,then*

$$\max_{p_1, p_2} \lambda_\rho(p_1, p_2) = \max_{p_2} \lambda_\rho(1, p_2).$$

When beacons are indistinguishable, let $p_1 = p_2 = p$*. Then,* $\max_p \lambda_\rho(p, p)$ *is a strictly decreasing function of* ρ*.*

From the above theorem, it is clear that the maximal throughput is achievable for any fraction of overlap below the threshold $\frac{1+\beta}{\beta}$. It is however surprising that the optimal transmission probability in the overlapping region is 0, inspite of the high probability of success in that region. The reason behind the phase transition is that, the throughput is only a function of mean transmissions in each region. Figure 3 demonstrates such a phase transition.

Since the throughput is only a function of mean transmissions (product of density, overlap and transmission probability) in each region, any overlap configuration is associated to a packet distribution for a fixed throughput. By packet distribution, we mean the fractions of total throughput received from overlapping and non-overlapping regions. We define the packet ratio $\psi = \frac{\lambda_1}{\lambda}$ where λ is the net throughput, and λ_1 is the throughput received from the overlapping region.

The results in [15] show that maximum efficiency was obtained when activation regions overlap completely, or in other words, when the packet ratio $\psi = 1$. The throughput from the network in that case, however, was infinitesimally small. Therefore, for a fixed non-zero throughput, the configuration that requires least number of transmissions may not be trivial. Since $\psi = 0$ is throughput optimal, intuitively, the packet ratio that maximizes efficiency would be inversely related to the throughput. Figure 4 plots the mean transmissions versus

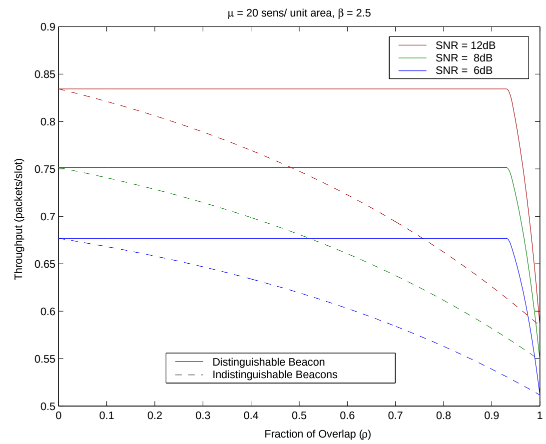

Figure 3: Throughput for network with two fixed APs

packet fraction for different throughputs. This figure confirms our intuition that the optimal packet fraction decreases with increase in throughput. Furthermore, since the energy is directly proportional to the mean transmissions, the figure indicates that the energy consumption is a convex function of the packet ratio.

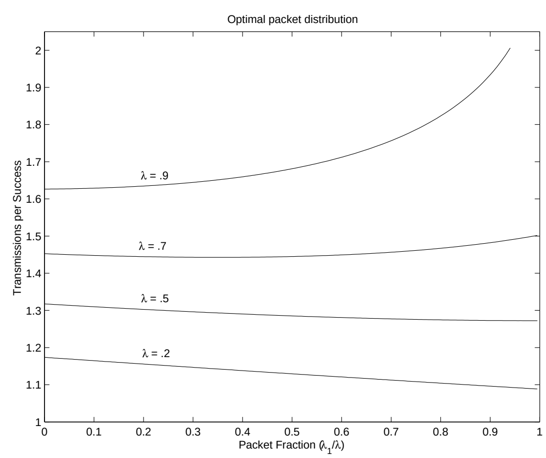

Figure 4: Mean Transmissions versus Fraction of packets from overlapping region

III. Cross Layer Optimization

From the theoretical analysis in the previous section, it is clear that, to maximize efficiency for a given throughput, it is necessary to distribute data across the network optimally, or choose AP locations such that activation region overlap optimally. In practice, however, the required throughput may vary from time to time and it is not possible to dynamically change the location of APs to maximize efficiency. Moreover, the distribution of data across the network is dependent on the phenomenon that has been sensed. In order to get a good reconstruction of the field, it is often necessary to draw packets from all parts of the network.

In practical situations, sensors may be required to route some of their data across regions to obtain an energy efficient packet distribution for the same required throughput. Routing requires a certain overhead apart from the energy consumed in the actual data transmission. This overhead may include initialization, route discovery and shortest path decisions. It is therefore necessary to design a cross layer strategy that optimally combines routing and AP transmission to minimize the total energy consumption. In this section, we focus on an analytical approach to the energy efficient data collection under the cross layer perspective. In section A, we describe the basic system model. In section B we obtain mathematical expressions for energy consumption in a two AP network. In section C, we use the derived mathematical expressions and obtain optimal strategies.

III.A System Model

Let us consider the two AP network as shown in Figure 5. The fraction of overlap ρ is fixed. The throughput required from the network is λ packets/slot. We restrict λ to throughputs that are achievable by any fraction of overlap (less than the minimax). The data are assumed to be uniformly distributed across the network. If we ignore stability issues, such a model would also cater to collection of data generated at a rate of λ that is uniformly distributed across the network.

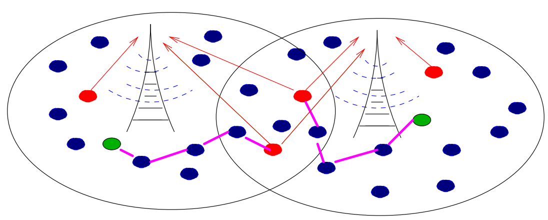

Figure 5: Cross Layer Data Collection Strategy

A fraction α of net data generated is routed from non-overlapping to overlapping region (α could be negative, indicating that routing is from overlapping to non-overlapping region). The packet distribution between the regions can be given by (λ_1, λ_2), where λ_1, λ_2 denote partial throughputs from overlapping and non-overlapping regions respectively. λ_1, λ_2 satisfy

$$\lambda_1 + \lambda_2 = \lambda, \tag{6}$$

$$\lambda_1 = \frac{\rho}{2-\rho}\lambda + \alpha\lambda. \tag{7}$$

The partial throughput λ_1 includes the datat generated in the overlapping region and those routed from outside. The transmission probabilities p_1, p_2 are chosen such that the above equations are satisfied using minimum average number of transmissions per slot.

The overall protocol is as follows. Whenever a sensor has data to transmit, with probability α', it routes the data to a sensor in the adjacent region. The probability α' is a function of α, ρ and the cross layer strategy employed.

$$\alpha' = \begin{cases} \frac{\alpha(2-\rho)}{\rho} & \text{overlapping to non overlapping} \\ \frac{\alpha(2-\rho)}{2(1-\rho)} & \text{non-overlapping to overlapping} \end{cases}$$

The scaling factors $\frac{\rho}{2-\rho}, \frac{2(1-\rho)}{2-\rho}$ are the ratios of areas of overlapping and non-overlapping regions respectively with the total area of the activated region. We assume sensors use the following routing protocol to discover routes. Each sensor randomly picks a small area in the destination region. We assume that the size of the areas are enough so that the probability of finding a sensor in each area is very high. The source node then floods a discover packet to the destination region. Once the discover packet reaches a node in the selected area, that node sends back a success packet along the route. To avoid multiple routes to the destination, the source node only considers the first success packet. This route is then used for the transmission of the current data.

The design of medium access control for the sensor-sensor transmission is not considered in this paper. If the transmission power is greater than a threshold, then the packet is assumed to be received error-free. In dense sensor networks, where the proximity of sensors is high enough to neglect fading effects, this model is a good approximation.

For a given fixed throughput λ, we need to devise a strategy for data collection (specify optimal α) that minimizes total energy. In the proceeding section, we characterize the energy consumption for this network model.

III.B Energy Analysis

Consider the network as shown in Figure 2. The area of activated region under each AP is assumed to be 1. If the density of awake sensors is μ and the fraction of overlap is ρ, then the average number of sensors awake is $N = \mu(2-\rho)$.

B.1 Sensor - AP Transmission Energy

The fraction of data routed from non-overlapping to overlapping region is given by α. We know that the throughputs from the two regions (λ_1, λ_2) satisfy equations (6) and (7). Therefore the probabilities of transmission (p_1, p_2) must satisfy :

$$\lambda_1 = 2e^{-\beta\sigma^2}\mu(1-\rho)p_1 e^{-\frac{\mu\beta(((1-\rho)p_1+\rho p_2))}{\beta}},$$

$$\lambda_2 = 2e^{-\beta\sigma^2}\mu\rho p_2 e^{-\frac{\mu\beta(((1-\rho)p_1+\rho p_2))}{\beta}}\left(1 - e^{-\beta\sigma^2}e^{\frac{\mu\rho p_2}{(1+\beta)^2}}\right).$$

Refer to proof of Theorem 1 for a derivation of above equations. As mentioned earlier, the throughput is a function of mean transmissions in each region, namely $(\rho\mu p_2, 2(1-\rho)\mu p_1)$. For further analysis, we shall use (n_1, n_2) to denote the mean transmissions in the overlapping and non-overlapping regions respectively. The ratio $\frac{P_T}{\sigma^2}$ refers to the mean of the received SNR of each packet. In accordance with our earlier assumption, the distance between sensor and AP has negligible variance across sensors in the activated region. This is a reasonable model, when the AP is at a significant height, or the size of each cluster is very small. If the distance between sensor and AP is taken to be h, and the slot is assumed to have unit duration, then each sensor transmission requires an energy of $P_T h^2$ to overcome path loss. If we assume each packet has M bits and E_b is the energy required per bit transmission through unit distance, then we can write the energy consumption per transmission as ME_bh^2. The total energy per slot is dependent on the mean transmissions per slot to sustain the throughput required and is given by:

$$E_{ap} = ME_b(n_1 + n_2)h^2 \text{J/slot}. \tag{8}$$

B.2 Routing Energy

To evaluate the energy consumption for routing, we follow the techniques used in [7]. We use a simple routing protocol to illustrate our analytical approach to the data collection problem. Moreover, the conclusions regarding optimal strategies, which we derive in the next section, are independent of the routing protocol used.

When a node decides to route the data to an adjacent region, it randomly picks a small area in the region. The network is assumed to be divided into $N\nu$ regions, where ν is chosen such that the probability of finding a sensor in each area is high enough. Each region can be identified using $\lceil \log N \rceil$ bits. Specifying a destination region instead of node ID has several advantages. Firstly, the approach is no longer affected by random sleep cycles of sensors. Secondly, the difficult task of obtaining co-ordinates of each node and distributing the information to the whole network is no longer required. Moreover, since these destination regions are randomly chosen by sensors, the total routed data can be uniformly redistributed across the transmitting region.

Each sensor transmits with enough power so as to reach nodes within a radius r. In accordance with the work in [14], the minimum r required for connectivity is given by $r = \sqrt{\frac{\log N}{N}}$. Therefore, each sensor consumes an energy $E_b r^2$ to transmit one bit to a neighbouring sensor. The energy required to listen and process data is comparitively very less and has been neglected.

Route Discovery: After a node has chosen a destination region, it floods a discover packet across the network. The discover packet contains the source ID, current node ID, destination region location, a field for number of hops (each can be specified using $\lceil \log N \rceil$ bits) and a 'DISCOVER' message ($O(1)$ bits). Since the flooding is done across the entire network, the total energy spent in transmitting 'DISCOVER' packets can be written as

$$E_1 = N\left(4\lceil \log N + O(1) \rceil\right) E_b r^2. \tag{9}$$

Each node in the path stores the source ID, destination region and the ID of the node from which it received the packet, before it transmits the packet further. Multiple packets for the same source destination pair may be heard by a node, in which case, the node considers packets that are heard within a finite time after the first packet, chooses the packet with least number of hops and ignores the rest. The nodes in the destination region follow a similar procedure, except, after the waiting time, they choose the path with least hops, and transmits a success packet along that path back to the source. The success packet contains the original source node and destination region IDs, the specific destination node ID, the current node ID and the 'SUCCESS' message. The average number of nodes in the destination region is $\frac{1}{\nu}$ which is equal to number of 'SUCCESS' packets sent back. We use $E(X)$ to denote the average distance between two nodes in non-overlapping and overlapping regions. Therefore, the average number of hops in a successful route is given by $\lceil \frac{E(X)}{r} \rceil$. Based on the above discussion, we write the energy consumed in the 'SUCCESS' packets transmission as

$$E_2 = \frac{1}{\nu}\lceil \frac{E(X)}{r} \rceil \left(4\lceil \log N + O(1) \rceil\right) E_b r^2. \tag{10}$$

Data Transmission: Once a route is established, the actual data transmission only requires the IDs of the destination node and next node in the path apart from the actual data packet itself. If the data packet length is asumed to be M bits, then the transmission energy is given by

$$E_{dt} = \lceil \frac{E(X)}{r} \rceil \left(2\lceil \log N \rceil + M\right) E_b r^2.$$

As specified in the system model, a fraction α of the throughput λ is routed across regions. The net energy required for routing is therefore

$$E_r = |\alpha| \lambda (E_1 + E_2 + E_{dt}) \text{J/slot}. \tag{11}$$

III.C Optimal Strategies

Given a network with a fixed fraction of overlap ρ and a required throughput of λ, our goal is to design α that minimizes the total energy given by $E_{net} = E_{ap} + E_r$.

In section II, we characterized the sensor-AP transmission energy as a function of packet fraction ψ. It was observed that the transmission energy is a convex function of ψ. The slope of the curve at $\psi = 1$ (represents zero transmission from non-overlapping region), increases with the net throughput λ. If we ignore routing energy, the optimal ψ is equal to 1 for low throughputs and decreases monotonically as throughput increases. Since, without routing, the fraction of data present in the overlapping region is $\frac{\rho}{2-\rho}$, the required design parameter α is related to ψ as

$$\alpha = \psi - \frac{\rho}{2-\rho}.$$

As discussed in section B.2, the routing energy is proportional to $|\alpha|$. Therefore, if the AP transmission energy is convex, the net energy consumption is also a convex function of packet fraction α. This can also be observed from Figure 6.

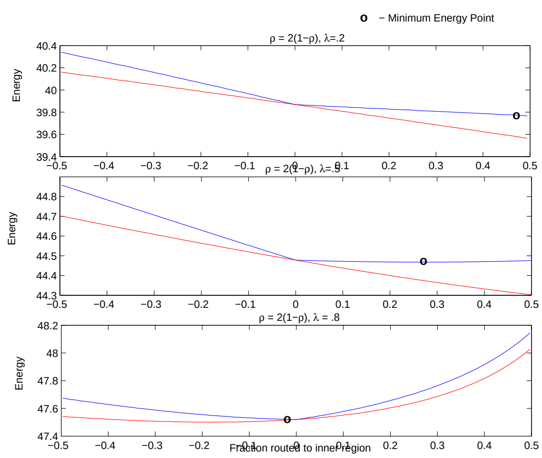

Figure 6: Energy vs α, Overlap = 1/2

Figure 6 plots the energy versus α for $\rho = 1/2$. From the figure, we can see that the optimal α is $1 - \frac{\rho}{2-\rho}$ (equivalent to $\psi = 1$) for low throughputs and decreases as throughput increases. The behaviour is similar to the situation when routing is not involved. The reason for this is that routing energy is also convex with a constant slope proportional to net throughput. The minimum α in each case is shifted, but the overall behaviour w.r.t net throughput is unaltered.

Figure 7 plots the optimal α w.r.t throughput. As observed earlier, the optimal α decreases with increase in throughput. The optimal α undergoes a phase transition at a fixed throughput independent of fraction of overlap ρ. The optimal strategy therefore, is to route completely to the overlapping region when throughput is low, and to not route at all, when throughputs are high. Routing to non-overlapping region occurs only under extremely high throughput regime and high fraction of overlap. This behaviour conforms to the theory that for low throughputs, transmissions from overlapping region are more energy efficient. When throughputs are higher, the difference in energy-efficiency between the two regions is not significant to include additional routing energy.

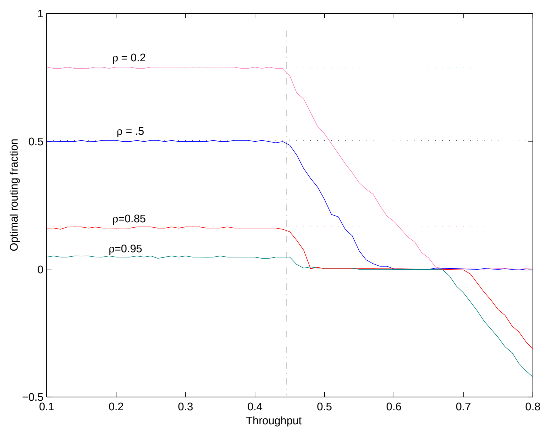

Figure 7: Optimal α vs Throughput

The intuitive reasoning for the phase transition is as follows. For low throughputs, the slope of sensor-AP transmission energy at $\psi = 1$ is negative, and increases w.r.t net throughput λ. The slope of routing energy is positive and also increases with λ. When λ increases, the net slope becomes positive and the optimal α decreases. Since the slopes are independent of fraction of overlap ρ, the phase transition point is identical for all configurations. The second phase transition that occurs in highly overlapped networks can also be explained using similar arguments. For any routing protocol, the behaviour of optimal α is the same. The phase transition point would depend on the routing scheme employed. This is because, the energy versus α curve for any routing scheme differs by a scaling factor.

IV. Conclusions and Further Ramifications

In this paper, we analyzed the data collection problem in sensor networks with multiple access points from an energy efficiency perspective. We developed cross-layer strategies that combine medium access and routing protocols and optimized the fraction of data that needs to be routed across the network. We showed that for low throughput requirement, all the data has to be routed to the overlapping region between APs. Whereas for higher throughputs, it is ideal not to route any data. When throughput requirement is very high, it is necessary to route data to non-overlapping region. This conforms to previous results [15] that transmissions from non-overlapping regions are throughput-optimal. The phase transition in optimal fraction of routing occurs independent of the routing protocol used.

Although we have used specific protocols in our analysis, this setup can be used to characterize the enrgy efficiency of other routing and MAC protocols as well. The design of an optimal routing strategy for this model is an interesting problem. Since the routing involved is between geographical regions, intuitively,we would expect location based protocols to be more suitable for this network model. In this work, we have also assumed that each packet that is routed is transmitted to the AP independently. One possible future extension would be to consider the problem of data combining at the sensor level before transmission to the AP.

Although the assumptions in this paper with regards to i.i.d fading and distribution of sensors are idealistic, we believe that the analytical approach can be suitable modified to design strategies under practical conditions.

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