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Joint Optimization of Age of Information and Energy Efficiency in IoT Networks

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***Abstract*—Age of information (AoI) refers to the freshness of data generated by a status-update system. It is a crucial metric in networks such as Internet of things (IoT), specially when the underlying application demands fresh update. In environmental monitoring and smart agriculture, apart from importance of AoI, energy efficiency (EE) becomes inevitable owing to network longevity. This paper studies an IoT network where the end devices transfer their information to a central gateway residing on a moving platform such as a tractor, which collects information from a large number of sensors in an agri-field. An optimal trajectory of the mobile reader is proposed using a modified nearest neighbour algorithm to gather the information from randomly distributed sensors. A clustering algorithm is also used to cluster the data in such a way that the overall EE of the network is maximized keeping a desired AoI and outage probability.**

***Index Terms*—Internet of Thing, smart agriculture, age of information, energy efficiency.**

I. Introduction

In the past few years, the Internet of Thing (IoT) technology has revolutionized various applications, whereas the number of applications of IoT is expected to increase exponentially in the near future. Some of the areas revolutionized by the IoT are smart cities, smart agriculture, smart homes and smart vehicles, etc. [1]. Most of these applications demand timely exchange of information from the sensors to the central aggregation point because most of the sensed information is time sensitive to perform a reactive operation [2]. The status updates generated at the environmental sensors should be delivered to the desired recipient as soon as possible, however, the timely delivery is usually compromised subject to limited resources of the network [2]. The emerging IoT applications have made the age of information (AoI) more important because of their requirement of fresh data [3]. AoI is a metric for timely delivery of information from source to the destination which is crucial because outdated information can cause inefficiencies in many applications specially those related to humans and other living things [2]. Traditional network metrics of throughput and delay are insufficient for maximizing the performance of status update systems. Therefore, AoI should be used which directly defines application layer performance of the age critical applications [4].

In wireless sensor networks, where the data is collected from the sensors for time sensitive applications, the information freshness can be measured using AoI [5]. For example, in agriculture, the smart systems which monitor crops must receive the status updates timely from the sensors deployed in the field. It is also important to collect information from the sensors in a cost efficient way. The information collector or the reader must cover maximum number of sensors and use the shortest path to acquire the information of all sensors as quickly as possible. The trajectory optimization is useful because it optimizes the AoI as well as the energy efficiency (EE) of the information collected from the sensors. Some of the applications not only demand fresh data but also high throughput and lower outage events. Therefore, it is crucial in some applications not to drop packets, such as latest news and social updates [6]. The AoI metric was first introduced by [7] in vehicular networks for end-to-end delivery of information for fresh data requirement of applications which broadcast data periodically. Timely exchange of information has gained a big interest in vehicular and IoT networks [8]. AoI is also been used in other applications like Unmanned Aerial Vehicles (UAVs). [9] uses a UAV as a mobile relay for timely delivery of status update between a source-destination pair. The link between source and destination node is considered to be weak. The flight trajectory is optimized to minimize AoI, energy and service time allocation. Simulation results show that the proposed algorithm in [9] performs well when the energy at source nodes and UAV is limited and the packet size is too large. [10] uses UAV to collect information from the IoT sensors. The authors proposed optimization of AoI by optimizing the flight trajectory of the UAV. The flight trajectory is optimized using the shortest Hamiltonian distance. Results show that the optimization of flight trajectory is proportional to the AoI.

Agriculture is a prime industry in rural areas. Most of the rural areas lack mobile communication infrastructure, which makes implementation of smart agriculture challenging. Use of UAVs is not an efficient way in rural areas as it need expert operators and is also not cost efficient. In our proposed method, we consider a conventional tractor which carries a reader that collects information from all the sensors in the field by visiting optimized locations. Use of tractor is an efficient way because it can also be used for multiple purposes simultaneously. The optimized locations are the centroids formed using a K-mean clustering algorithm, however the number of clusters is a design parameter that affects both EE

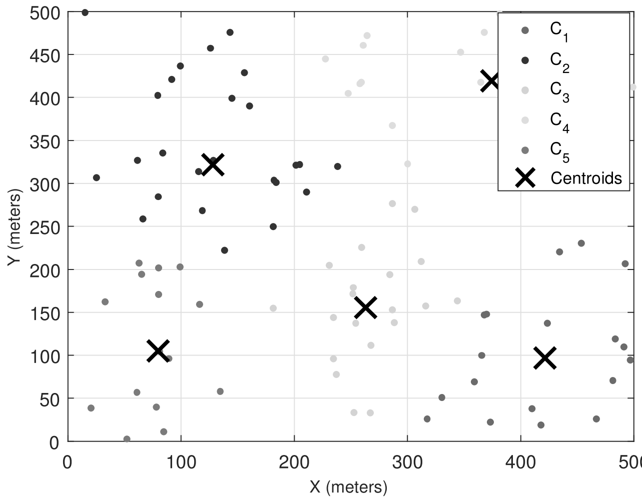

Fig. 1: Distribution of sensors in 500x500 m^2 area

and AoI. The tractor is supposed to follow a nearest neighbour algorithm to visit each cluster formed by K-mean clustering. We optimize the number of clusters to maintain a target AoI and EE while keeping a desired outage probability.

The rest of the paper is organized as follows. Section II outlines the system model and the network layout whereas the optimization of AoI and EE is discussed in Section III. We then proceed to highlight the numerical results and their discussion in Section IV. The paper finally concludes in Section V.

II. System Model

Consider a square-shaped agricultural area of dimension 500x500 m^2 with N IoT sensors deployed randomly in the area as shown in Fig. 1. A mobile reader collects information from all the deployed sensors by visiting different points in the field. The main objective is to gather information from maximum number of sensors in a minimum time while achieving maximum energy efficiency.

This proposed model uses the K-mean clustering algorithm to group the sensors, which partitions the distributed sensors in to K clusters where every sensor belongs to a cluster having the nearest mean. Suppose the set of deployed sensors is $\mathbb{S} = \{\mathbf{S_1}, \mathbf{S_2}, ..., \mathbf{S_N}\}$ where each $\mathbf{S}_n, n \in \{1, 2, ...N\}$ is a two dimensional vector containing the (x, y) location of the n^{th} sensor. The K-mean algorithm divides N sensors in to K clusters such that, $\mathbb{C} = \{C_1, C_2, ...C_K\}$ is the set of clusters and $K < N$. The objective is to find

$$\underset{\mathbb{C}}{\mathbf{arg}\min} \sum_{i=1}^{K} \sum_{\mathbb{S} \in \mathbf{C_i}} || \ \mathbb{S} - \boldsymbol{\mu_i} \ ||^2, \tag{1}$$

where $i = \{1, 2, ...K\}$ and $\boldsymbol{\mu_i}$ denotes a two dimensional vector containing the mean of set of sensors deployed in the cluster C_i and is the (x, y) coordinates of the cluster head for that particular cluster. The expression (1) iteratively finds the optimum location of the cluster heads or centroids. In Fig. 1, C_1, C_2, C_3, C_4 and C_5 with different colors show the sensors associated with different clusters, while cross signs show the centroids of the clusters. In the proposed algorithm, without the loss in generality, the reader starts collecting information from the lowest leftmost centroid in Fig. 1 and then moves to the next centroid using a *nearest neighbor algorithm.* The nearest neighbour algorithm optimizes path by visiting the node with shortest path first. In our methodology, the reader first computes its Euclidean distance to all other cluster heads and moves to the cluster head with minimum distance. This process continues until all the centriods are visited by the reader. In the next section, we discuss the up-link received power model and the AoI optimization.

III. AoI and EE Optmization of the Network

Suppose, the reader is placed at centroid of i^{th} cluster. Then the reader first measures Euclidean distances to all other cluster heads and then moves to the cluster having minimum distance. On each cluster, the sensors associated with that C_i transmit information to the reader with transmit power P_t. The reader receives the information from all the sensors and compares the received power to a decoding threshold, τ. Each sensor transmits its information to the reader using a pre-defined multiple access technique such as time division multiple access (TDMA) or non-orthogonal multiple access (NOMA) [11]. The received power from the n^{th} sensor to the reader is given as

$$Pr_{n,i} = \frac{P_t}{d_{n,i}^{\alpha}}, \tag{2}$$

where the transmit power, P_t, is assumed equal for all sensors and α in the above equation represents the path-loss exponent. The $d_{n,i}$ denotes the Euclidean distance of the n^{th} sensor in i^{th} cluster to its centroid. Without the loss of generality, we assume unit noise power spectral density, then the up-link data rate of the n^{th} sensor of i^{th} cluster is given as,

$$R_{n,i} = Blog_2(1 + SNR_{n,i}), \tag{3}$$

where $SNR_{n,i}$ is the received signal-to-noise ratio (SNR) from n^{th} sensor of i^{th} cluster, i.e., $SNR = Pr_{n,i}/\sigma^2$, where $\sigma^2 = 1$ and B denotes the systems bandwidth. As the number of clusters increases, the energy efficiency and coverage increase but the AoI also increases. We need an optimal size of set $\mathbb{C}$, i.e., number of clusters, which covers maximum number of sensors with minimum AoI. Outage probability in each cluster can be found comparing the received power of each sensor with the threshold τ, which is given as

$$P_{out} = \mathbb{P}\{Pr_{n,i} < \tau\}, \tag{4}$$

where $Pr_{n,i}$ is the received power at the reader placed at i^{th} cluster head from n^{th} sensor in that cluster.

EE is defined as the ratio of achieved sum-rate and total transmit power. In this research, one of our objectives is to maximize energy efficiency by increasing the number of

TABLE I: Simulation Parameters

Parameter	Value
Transmit Power P_t	15 dBm
Path-loss α	2
Speed of reader v	20 Kmh^{-1}
Number of sensors N	100
τ	-30 dBm
K-mean iterations	10
Bandwidth B	1 Hz
γ	0.1

clusters and minimizing the outage probability. For N sensors having same transmit power, EE is defined as

$$EE = \frac{1}{P_t} \sum_{i=1}^{K} \sum_{n=1}^{N} R_{n,i}. \tag{5}$$

We now revert our discussion to AoI. The relationship between the speed of the reader and distance travelled by the reader represents the time elapsed between the service times of the sensors of a cluster. This could be attributed as the time for which the sensors hold information for transmission to the reader. In the proposed method, AoI at the starting cluster is considered to be zero and is measured on all other centroids as the time taken by the reader to move from the first centroid to the last centroid, which depends on the speed of the reader and the distance travelled. Mathematically, the AoI can be defined as

$$AoI = \frac{1}{v} \sum_{i \in \mathbb{C}}^{K-1} \tilde{d}_i, \tag{6}$$

where v is the speed of the reader and $\tilde{d}_i$ is the Euclidean distance between $(i+1)^{st}$ cluster head and the i^{th} cluster head. Our objectives are to minimize the AoI, minimize the outage probability and to maximize the EE of the system. The objectives function can be written as

$$\min \quad AoI \tag{7}$$

$$\max \quad EE \tag{8}$$

subject to

$$Pr_{out} < \gamma \tag{9}$$

where γ is the quality-of-service (QoS) requirement of outage probability. Our objectives of maximizing EE can be achieved by increasing the number of clusters, however, increasing the number of clusters increases the AoI as the reader has to traverse more number of centroids. Therefore, an optimal number of clusters are required, which satisfies our objectives. The proposed optimization scheme is also depicted as Algorithm 1 in the paper.

Algorithm 1 Proposed Algorithm

Input: $\mathbb{S}$,$\mathbb{C}$,τ,P_t
Output: AoI, EE
Create a set of clusters $\mathbb{C}$ using Equation (1)
for $i = 1$ ***to*** $\mathbb{S}$ **do**
    Find distance $d_{n,i}$ of n^{th} sensor to its cluster-head c_i
    Find $Pr_{n,i}$ at reader placed at cluster-head from each sensor using (2)
    if *($Pr_{n,i} \geq \tau$)* **then**
        Find data rates $R_{n,i}$ using Equation (3)
        Find outage Probability using (4)
    end
    else
    end
    for $j = 1$ ***to*** $C_j - 1$ **do**
        Find Euclidean distance $\tilde{d}_j$ to all other cluster-heads and move to cluster-head with minimum $\tilde{d}_j$ using nearest neighbour algorithm
    end
end
Compute AoI and EE using Equation (5) and (6), respectively

IV. SIMULATION RESULTS AND DISCUSSIONS

This section discusses the effect of number of clusters on outage probability, EE and AoI. The field area, number of sensors and transmit power are the constraints which determine an appropriate number of cluster to accomplish the quality of service requirements. The parameters used for simulation are shown in Table I.

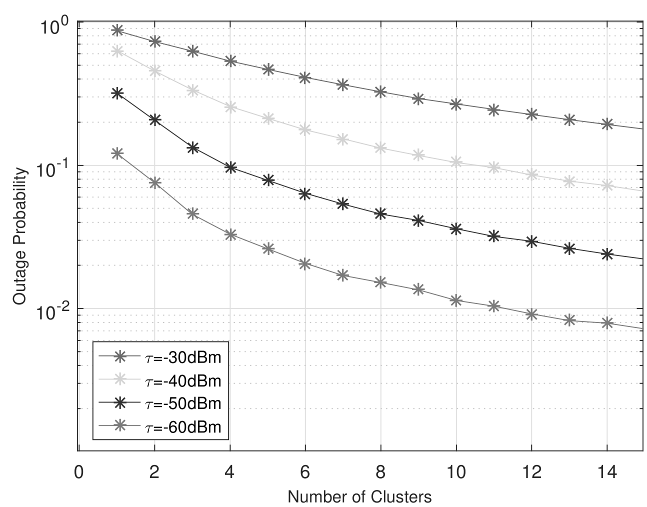

Fig. 2: Outage probability for different number of clusters

Fig. 2 depicts the outage probability of the network versus the variation of number of clusters for 500x500 m^2 area for different threshold values. Clearly when the number of clusters increases, the radius of each cluster decreases which reduces the distance of sensors to the reader and hence the outage probability decreases. Similarly, a lower value of threshold decreases the outage probability further.

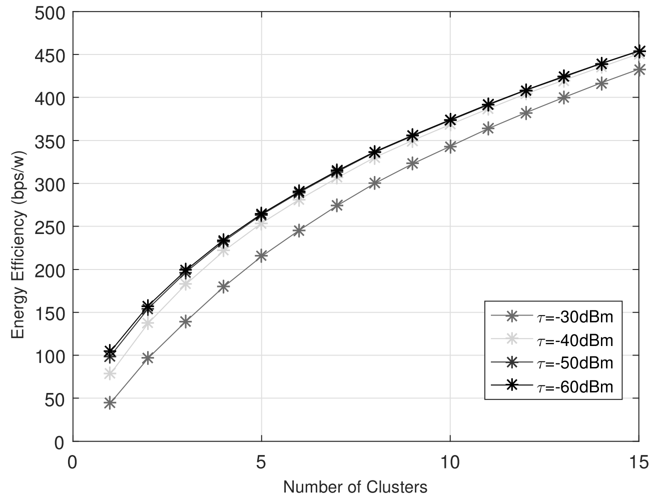

Fig. 3: EE for different number of clusters

The EE calculated using (5) is compared with different number clusters as shown in Fig. 3. The figure shows that the EE of the system increases with the increase in the number of clusters because with more clusters, the coverage area increases and hence the sum-rate increases. However, the EE starts to saturate at a particular point depicting that after a specific number of clusters, there is no substantial increase in the sum-rates.

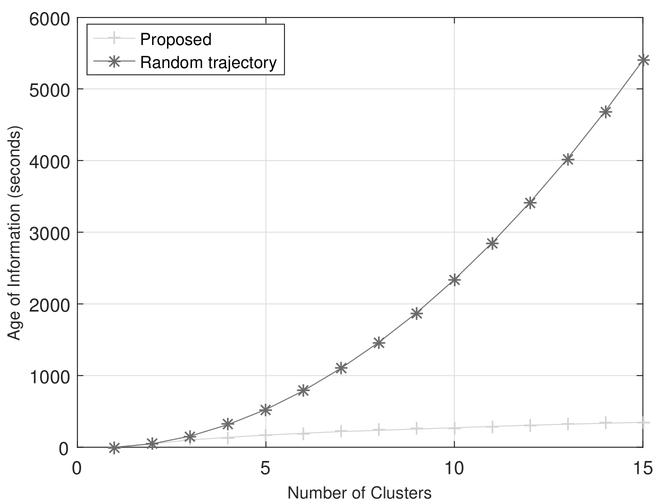

Fig. 4: AoI for random trajectory vs proposed method

Fig. 4 compares the AoI of the proposed method in which the tractor follows a random path. The AoI increases with the number of clusters because the reader has to move extra distance. Fig. 4 shows that the proposed method outperforms the random trajectory in minimizing AoI. The proposed method uses the nearest neighbour algorithm to follow shortest distance while moving to next centroid and hence decreases the AoI as compared to the random trajectory method.

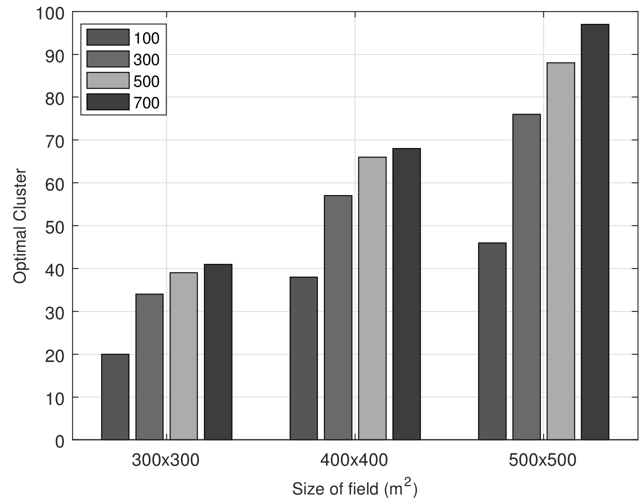

Fig. 5: Optimal Clusters for min EE=200 bps/W, max AoI=900 seconds and outage probability$< \gamma$

We set a QoS requirement of AoI, EE and outage probability to obtain an optimal number of required clusters for our model. Fig. 5 shows the results simulated for a condition when we require minimum EE of 200 bps/W, can afford up to 900 seconds of AoI and outage probability must be less than 10%. The graph shows that to maintain the QoS requirements, when the total number of sensors in an area increases, the required number of clusters also increases. For example, we can see that to meet the QoS requirement for 100 sensors and 300x300 m^2 area, we will require 20 clusters to meet the QoS requirements.

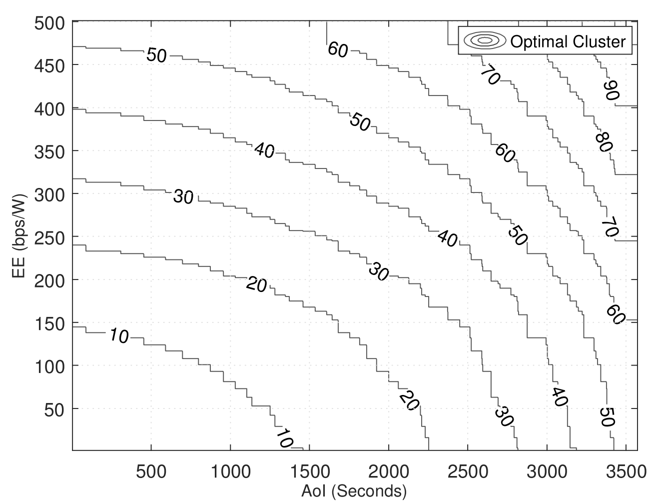

Fig. 6: Optimal Clusters for 500x500 m^2 area

Fig. 6 shows the optimal number of clusters against EE and AoI for an area of 500x500 m^2 and N=100. It can be observed that when an application can afford up to 1500 seconds AoI, the maximum EE to be achieved is approximately 145 bps/W using 10 clusters while keeping 0.1 outage probability. Fig. 7

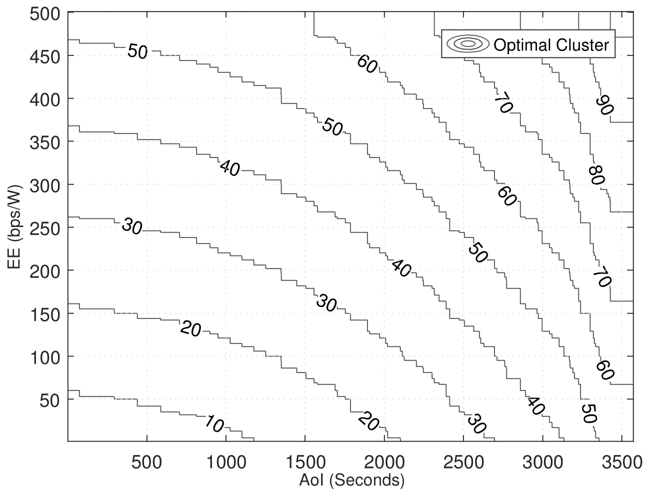

Fig. 7: Optimal Clusters for 1000x1000 m^2 area

shows the same results for increased area of 1000x1000 m^2 and the number of sensors kept constant, i.e, N=100. To get the previously obtained results of AoI and EE, we can see that we will require almost 20 clusters to maintain the same QoS of 200 bps/W EE and less than 1500 seconds of AoI.

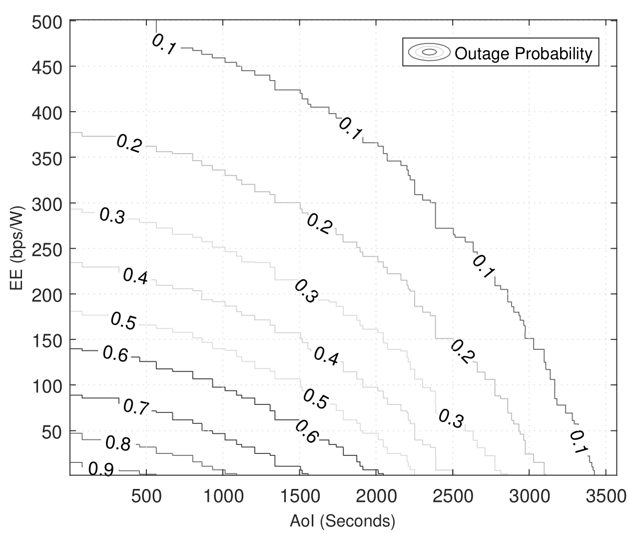

Fig. 8: Outage probability for 1000x1000 m^2 area

Fig. 8 shows the contours of outage probability of an area of 1000x1000 m^2, where the number of clusters is 15 and 100 sensors. It can be observed that for a desired EE of say 100bps/W and a minimum desired AoI of 1500 seconds, the corresponding outage probability is 0.6, which is very large. Therefore, we need more than 15 clusters to meet the requirements of outage probability as well as desired AoI and EE.

V. Conclusion

In this paper, we studied the importance and optimization of age of information and energy efficiency in IoT networks. We used K-mean algorithm to cluster the deployed sensors in an area and then used the nearest neighbor algorithm to move the reader from one cluster to another. K-mean clustering and nearest neighbor algorithms jointly outperforms the random trajectory traversing in optimizing the AoI without much affecting the EE and outage probability. We optimized the number of clusters in an area to get the desired AoI and EE with desired probability outage. As a future work, we intend to combine the proposed model with backscatter communications to study the behavior of AoI on the performance of energy-constrained networks.

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