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APPENDIX A

A.1 Expected Distance between Two Immediate Neighboring Nodes

The expected distance $\bar{D}$ of any two adjoining sensor nodes can be calculated using the fact that the ad-hoc deployed nodes are distributed as a 2D Poisson point process with intensity λ. The random distance D between a node and its nearest neighbor node is determined first. For $x > 0$, the cumulative PDF of D is given by

$$F_D(x) = P(D \leq x) = 1 - P(D > x)$$

itself)

Hence, the PDF of D can be derived as

$$\begin{aligned} f_D(x) &= \frac{dF_D(x)}{dx} \\ &= 2\lambda\pi x e^{-\lambda\pi x^2} \end{aligned}$$

Therefore, the expected distance $\bar{D}$ between any two adjoining sensor nodes can be denoted by

$$\begin{aligned} \bar{D} &= \int_0^\infty x f_D(x) dx \\ &= \frac{1}{2\sqrt{\lambda}} \end{aligned} \tag{A.1}$$

A.2 Energy Optimum Cluster Head Location in an Arbitrary Cluster

It will be assumed that there are $N(>> 1)$ number of sensor nodes uniform randomly deployed in an arbitrary cluster area A resulting a Poisson point process with intensity $\lambda = N/A$. Further, it is assumed that the cluster head is located at (x_0, y_0) location with

respect to Cartesian coordinate system. Hence, the total energy cost of transferring ℓ bits of data to the cluster head from all non cluster head nodes can be given by,

$$S = \sum_{i=1}^{N} \left(E_{elec} + \epsilon_{amp} \left((x_i - x_0)^2 + (y_i - y_0)^2 \right)^{\frac{n}{2}} \right)$$

Therefore, the expected value of S denoted by $\bar{S}$ can be derived using Theorem 1 of [57] derived by Campbell's Theorem as

$$\bar{S} = \iint_A \frac{N}{A} \left(E_{elec} + \epsilon_{amp} \left((x - x_0)^2 + (y - y_0)^2 \right)^{\frac{n}{2}} \right) \, dx \, dy$$

In order to find the minimum $\bar{S}$, it is necessary to find

$$\frac{\partial \bar{S}}{\partial x_0} = 0 \quad \text{and} \quad \frac{\partial \bar{S}}{\partial y_0} = 0.$$

It can be safely assumed that, the intra cluster communication follows Free Space radio propagation model, i.e. $n = 2$. Then $\bar{S}$ will be minimized when

$$x_0 = \iint_A \frac{x \, dx \, dy}{A} \quad \text{and} \quad y_0 = \iint_A \frac{y \, dx \, dy}{A}$$

This implies that the cluster head should be located at the geometric centre of the cluster area.

A.3 Gl Role Delegation

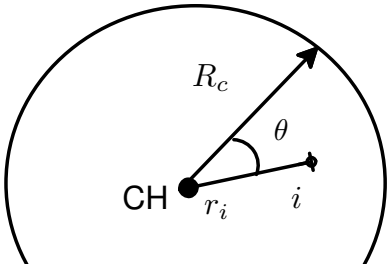
Cluster heads consume more energy than non cluster head nodes. Hence, cluster head role should be rotated among all nodes to facilitate even energy expenditure by all nodes in the sensor network. This can be done in two methods. First method is re-clustering of the entire sensor network (global re-clustering) whenever the cluster head role to be rotated. The main advantage of this method is that it allows cluster heads to be placed closed to the geometric centre of their cluster, resulting lesser total transmission energy for intra cluster communication. However, there is an energy cost for re-clustering. The second method is once cluster boundaries are determined cluster head role is delegated among nodes within the cluster (local delegation). The advantage of this method is that its low energy overhead in cluster head role rotation compared to global re-clustering. However, the main drawback of this method is that most of the time cluster head location is skewed, resulting a higher energy for intra cluster communication. In what follows, most suitable technique (global re-clustering or local delegation) for a given condition will be examined.

For this analysis, it will be assumed that the cluster head role is periodically rotated after a fixed x number of data gathering rounds. Further, it is assumed that the cluster

area is a circle with radius R_c and all nodes are uniform randomly distributed in this area, resulting a Poisson point process with intensity λ. Hence, the expected number of nodes in the cluster to be $N_n = \pi R_c^2 \lambda$. The word Epoch is defined as the total time which allows all nodes to function as a cluster head once. Hence, an Epoch consists of xN_n number of total data gathering rounds. The main difference in total energy cost per an Epoch in global re-clustering and local delegation is the intra cluster communication cost and cluster head role rotation overhead.

Global Re-clustering

It is assumed that the cluster heads always at the centre of their respective clusters, i.e. at the centre of the circle with radius R_c as shown in Figure A.1.



er

The total intra cluster energy cost in any one data gathering round can be denoted as $E_{0,0}$ where cluster head is at the centre of its cluster (Without loss of generality, centre of the cluster is consider as the $(0, 0)$ location). This will be given by,

$$E_{0,0} = \sum_{i=1}^{N_n} \left(E_{elec} + \epsilon_{amp} r_i^n \right) \ell$$

Therefore, the expected total value of $E_{0,0}$ given by $\bar{E_{0,0}}$ can be written using Theorem 1 of [57] derived using Campbell's Theorem as,

$$\begin{aligned} \bar{E_{0,0}} &= \ell\lambda \int_0^{2\pi} \int_0^{R_c} \left(E_{elec} + \epsilon_{amp} r^n \right) r \; dr \; d\theta \\ &= 2\lambda\pi R_c^2 \ell \left(\frac{E_{elec}}{2} + \frac{\epsilon_{amp} R_c^n}{n+2} \right) \end{aligned} \tag{A.2}$$

Total energy cost of intra cluster data gathering and cluster maintenance overhead during an Epoch will be denoted as E_{TGR}. Hence,

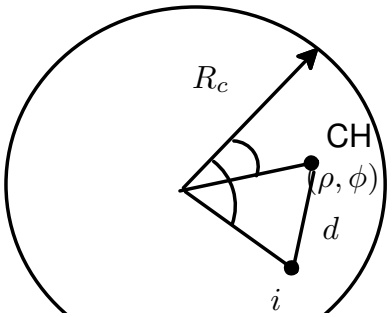
$$\begin{aligned} E_{TGR} &= N_n x \bar{E_{0,0}} + N_n \left(E_{CHohGR} + (N_n - 1) E_{nonCHohGR} \right) \\ &= \pi R_c^2 \lambda x \bar{E_{0,0}} + \pi R_c^2 \lambda \left(E_{CHohGR} + \pi R_c^2 \lambda E_{nonCHohGR} \right) \end{aligned} \tag{A.3}$$

where, E_{CHohGR} and $E_{nonCHohGR}$ refers to the energy overhead in re-clustering for a cluster head node and non cluster head node respectively (in global re-clustering).

Local Delegation

Now, total energy cost of intra cluster data gathering and cluster maintenance overhead, during an Epoch will be determined, when the clusters are maintained using local cluster head role delegation.

It is assumed that, at a given moment, cluster head is located at (ρ, ϕ) location and any node i is located at (r, θ) location with respect to polar co-ordinate system as shown in Figure A.2. If the distance between any node i and its cluster head is denoted as d_i, then



F ıtion

this can be ε

$$d_i = \left(r^2 + \rho^2 - 2r\rho\cos(\theta - \phi)\right)^{\frac{1}{2}} \tag{A.4}$$

Total intra cluster energy cost in one data gathering round can be denoted as $E_{\rho,\phi}$, where (ρ, ϕ) is the location of the cluster head. This can be given by

$$E_{\rho,\phi} = \sum_{i=1}^{N_n} \left(E_{elec} + \epsilon_{amp} d_i^n\right) \ell$$

Therefore, the expected value of $E_{\rho,\phi}$ denoted by $\bar{E_{\rho,\phi}}$ can be given using Theorem 1 of [57] derived by Campbell's Theorem as,

$$\bar{E_{\rho,\phi}} = \lambda\ell \int_0^{2\pi} \int_0^{R_c} \left(E_{elec} + \epsilon_{amp} \left(r^2 + \rho^2 - 2r\rho\cos(\theta - \phi)\right)^{\frac{n}{2}}\right) r \; dr \; d\theta \tag{A.5}$$

Total energy cost of intra cluster data gathering and cluster maintenance energy cost during an Epoch can be denoted as E_{TLD}.

$$E_{TLD} = E[x \sum_{j=1}^{N_n} \bar{E_{\rho_j,\phi_j}}] + N_n\left(E_{CHohLD} + (N_n - 1)E_{nonCHohLD}\right)$$

Therefore, again using Theorem 1 of [57] derived by Campbell's Theorem,

$$E_{TLD} = x\lambda \int_0^{2\pi} \int_0^{R_c} E_{\rho,\phi}\rho \; d\rho \; d\phi + \pi R_c^2 \lambda \left(E_{CHohLD} + \pi R_c^2 \lambda E_{nonCHohLD} \right) \tag{A.6}$$

where, E_{CHohLD} and $E_{nonCHohLD}$ refers to the energy overhead in cluster head role rotation for a cluster head node and non cluster head node respectively when the local cluster head role delegation is employed as the mechanism of cluster head role rotation.

Now, the conditions which would make a typical global re-clustering to be more energy efficient than local delegation is tested. For this, following assumptions are considered.

1. Intra cluster communication follows Free Space communication model, i.e. $\epsilon_{amp} = \epsilon_{amp-fs}$, $n = 2$.

2. It is possible to neglect the energy overhead in local cluster head role delegation, i.e. $E_{CHohLD} \to 0$ and $E_{nonCHohLD} \to 0$.

Hence, E_{TGR} and E_{TLD} can be simplified as follows.

$$E_{TGR} = xN_n^2 \ell \left(E_{elec} + \frac{\epsilon_{amp-fs} R_c^2}{2} \right) + N_n \left(E_{CHohGR} + N_n E_{nonCHohGR} \right)$$

Therefore,

$$E_{TLD} \qquad \qquad GR)) \tag{A.7}$$

If a typical use case is considered where $N_n = 20$, $R_c = 30$, cluster head would have about 10 overhead messages and a none cluster head have 2 overhead messages each with ℓ number of bits then,

$$E_{CHohGR} = 10 \left(E_{elec} + \epsilon_{amp-fs} R_c^2 \right) \ell + 2 N_n E_{elec} \ell$$

$$E_{nonCHohGR} = 2 \left(E_{elec} + \epsilon_{amp-fs} R_c^2 \right) \ell + 10 E_{elec} \ell$$

Further, it is known that $\epsilon_{amp-fs} = 10pJ/bit/m^2$ and $E_{elec} = 50nJ/bit$. Based on these numbers, $E_{TLD} - E_{TGR} \geq 0$ when $x \geq 5.1$. Hence, global re-clustering is more energy efficient as in practice $x >> 1$.