An Analysis on Adaptive Cluster Ratio in Wireless Sensor Networks

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ABSTRACT

Clustering schemes have been adopted as efficient solutions to prolong network lifetime and improve network scalability. In such clustering schemes cluster ratio is represented by the rate of the number of cluster heads and the number of total nodes and affects the performance of clustering schemes. In this paper, we mathematically analyze relation between cluster ratio and path loss in a cluster and an optimal cluster ratio is developed to provide promising channel and minimize packet loss. We examine its performance through a set of simulations. The simulation results show that the proposed optimal cluster ratio effectively guarantees packet reception rate in WSN.

Categories and Subject Descriptors

C.2 [**Computer communication networks**]: Wireless communications

General Terms

Design, performance

Keywords

WSN, cluster ratio, path loss, packet reception rate

1. INTRODUCTION

A wireless sensor network (WSN) consists of a large number of sensor nodes which equipped microprocessors, tiny memory, sensing devices and radio transceivers, densely deployed in a sensing region. In order to cooperatively accomplish a sensing task, sensor nodes have not only sensing, but also processing collected data, and communicating with neighborhood capabilities. When sensor nodes deployed, they must be able to autonomously communicate with nearby nodes over a short distance via wireless medium.

In some application case, sensor nodes are deployed for monitoring a target area where is impossible to be detect by human or providing a barrier coverage instead of traditional castles. Because of special application characteristic, these sensor nodes are typically small form factor battery powered and it is difficult to be changed or recharged for sensor nodes. Therefore, battery energy is a very scarce resource for such sensor nodes. In order to prolong the sensor nodes life as far as possible the resource must be utilized advisably.

ICUIMC '12 February 20-22, 2012, Kuala Lumpur, Malaysia

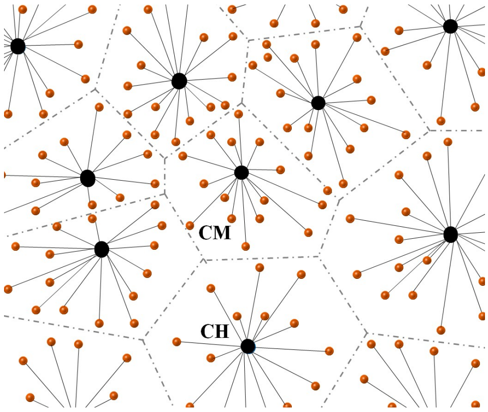

Figure 1: Single-hop clustering architecture

There are many energy efficiency mechanisms such as specific MAC and Routing protocols for WSN to provide extended network lifetime. Furthermore, for extending the network lifespan, sensor nodes can be assembled into groups i.e. clusters. Fig. 1 shows homogenous sensor network architecture with hierarchical topology based on a clustering scheme. CMs (Cluster Members) send their sensed data to CHs (Cluster Head) which have ability to process received data before transmitting to a base station or a sink. In that scheme, scalability can be improved by organizing sensor nodes into clusters when the network size grows. In addition data aggregation process in the CHs can reduce redundant information transmitted while sensed data have a certain level of correlation such as temperature or pressure monitoring applications. Owing to these benefits, clustering scheme has been adopted as one of effective solution to extend WSN life time and accomplish target tasks.

The most well-known clustering algorithms are LEACH and HEED. LEACH (Low-Energy Adaptive Clustering Hierarchy) is one of most early proposed hierarchical routing protocol. It's not only consider local CHs operate as router to base station but also exhibit an energy efficient clustering scheme that forms node clusters based on received signal strength. Before starting LEACH algorithm, an initial CR (Cluster Ratio) value needs to be defined. CHs to be elected according to a threshold value which is calculated by the initial CR. This leads to reduce the number of transponders, and enhance lifetime of the network. Election of CHs is random, and therefore it is hardly guarantee energy consumption balance among all nodes. That drawback has been improved in HEED (Hybrid, Energy-Efficient and Distributed) clustering scheme. It is different from LEACH on the selection criteria of the CH and introducing remaining energy of sensor nodes as a parameter to HEED.

However, both of LEACH and HEED suppose a static initial CR which means percentage of CHs in WSN. In this paper, we find that an improper CR may lead to excessive path loss and energy consumption between CMs and CH. We object to minimize data loss and reduce energy consumption occurs in communication between the correspondents. We develop a formula to analyze logical cluster size and prove that the CR impact on path loss in clusters. A threshold value is derived to provide a promising channel state, and then we obtain an optimal CR which can guarantee the expected PRR (Packet Receive Rate). Simulation results indicate that the proposed optimal CR effectively guarantees the PRR which means minimizing retransmission in a cluster.

The rest of the paper is organized as follows. In Section 2, we briefly review related work. We then formulate the optimal CR problem in Section 3. A set of simulation results and analysis present in Section 4. Finally, Section 5 contains the conclusion of the paper.

2. RELATED WORKS

Energy efficient of the clustering algorithms for WSN largely affects the energy consumption and network lifetime of WSN. Due to reducing data redundant and transmission times by its specific characteristic, the clustering algorithms observably prolong network lifetime. Heinzelman et al [1] proposed an energy efficient clustering algorithm for WSN which called LEACH. In LEACH the cluster head selected by a random mechanism. A factor defined as the initial CR p_{leach}, is set before starting this algorithm. In initial step, each sensor nodes select a random α in range of 0 to 1. If α is less than a threshold value $T(n)$ for node n, node n which belong to the set (G) of sensor nodes will elected as a CH for the current round r, otherwise, it become CM. This threshold value calculated as follows:

$$T(n) = \begin{cases} \frac{p_{leach}}{1-p_{leach}(r \bmod (1/p_{leach}))} & \text{if node } n \in G \\ 0 & \text{otherwise.} \end{cases} \quad (1)$$

LEACH has many advantages such as self-configure cluster, localized control for CMs, and easy operation. However, due to using static initial CR and the random mechanism to elect CH, it is hard to guarantee the enough number of CHs and homogeneous energy consumption among all nodes. Furthermore, it neglects remaining energy of the sensor nodes to cause low energy node to elect as a CH. These drawbacks improved by HEED [2] which is one of LEACH based clustering algorithm. It adapts to distribute energy consumption, minimize control overhead, and produce well-distributed cluster heads. As in LEACH, an initial CR, C_{prob}, is predefined, and then each sensor node sets probability CH_{prob} of becoming a CH.

$$CH_{prob} = C_{prob}\frac{E_{residual}}{E_{max}} \quad (2)$$

Where, $E_{residual}$ is remaining energy and E_{max} is maximum energy capacity in this sensor node.

Babaie et al [3] proposed a novel energy adaptive protocol develop a threshold value which based on both of LEACH and HEED. The threshold value calculated as follows:

$$T(n) = \begin{cases} \frac{p_{ncacm}}{1-p_{ncacm}(r \bmod (1/p_{ncacm}))} * \frac{E_{residual}}{E_{max}} \\ 0 \end{cases} \quad (3)$$

All of above these papers, there are no in-depth analysis on an optimal cluster and they set the CR as a static value to 5%. Through mathematically analysis on the optimal CR, we find that the CR impact on packet reception ratio in WSN in addition to path loss between correspondents. We proposed an optimal cluster ratio with object of guaranteeing an expected packet receive probability.

3. PROPOSED SCHEME

We consider a homogenous WSN consist of a large number of sensor nodes, which are densely deployed over an unattended area either close to or inside the targets to be observed. Sensor nodes are random deployed by Poisson distribution. Clusters are created by signal strength which means each cluster consists of a CH at the cluster center and the CMs that are closest to the CH and distributed around the CH.

To develop a formula for analyzing the impact of CR on the path loss in a cluster, we make the following assumption:

- Sensor nodes are distributed according to a homogeneous spatial Poisson process with intensity ρ.
- The CR is p, where $p = M_{CH}/M_t$. Distribution intensity of CHs can be calculated as $\rho_1 = M_r p/A$. M_t, M_{CH} and A indicate the total number of sensor nodes, the number of CHs and the field areas, respectively.
- Sensor nodes transmit with a uniform transmitting power P_t.
- CMs which distributed with intensity $\rho_0 = \rho(1-p)$ communicate with the CH through single-hop transmission, and the CMs and CH have a clear, unobstructed LoS (Line of Sight) path between them.

Using the idea of Foss [4], when $f(x_i)$ is a non-negative function, the first moment of aggregate characteristics $S_f = \sum_{x_i} f(x_i)1\{x_i \in \prod_0\}$ can be given as:

$$E(S_f) = \rho_0 \int f(x)e^{-\rho_1 \pi |x|^2} dx \quad (4)$$

Taking $f(x) = 1$ and $f(x) = l$ (where l is the link length between correspondents), we can get the expectations of the number of CMs (M_{CM}) and the total link length (L_t) of all CMs connecting to the nucleus CH in a cluster as Eqs. (5) and (6), respectively:

$$E(M_{CM}) = \frac{\rho_0}{\rho_1} \quad (5)$$

$$E(L_t) = \frac{\rho_0}{2\rho_1^{3/2}} \quad (6)$$

According to Eqs. (5) and (6), logical cluster size which means average distance between the CMs and CH in a cluster can be expressed as follow:

$$E(L_a) = \frac{E(L_t)}{E(M_{CM})} = \frac{1}{2\sqrt{\rho_1}} \quad (7)$$

Based on the previous assumption $\rho = M_r p/A$, $E(L_a)$ also can be expressed as:

$$E(L_a) = \sqrt{\frac{A}{4M_t p}} \quad (8)$$

Eq. (8) clearly describe that there are two factors, the total number of sensor nodes and CR, impact on the logical cluster size when the field areas fixed. In the case of LEACH which the optimal CR is configured as a static value of 5%, increase in M will lead to aggravating path loss and packet retransmission which is the reason of additional energy consumption in a cluster due to the variable logical cluster size. The next paragraph, we will describe the impact of the logical cluster size on packet retransmission.

In this paper, we neglect shadow fading and consider an outdoor-line-of-sight environment that using following propagation model [5] to predict path loss (P_L) in WSN.

$$P_L(d) = P_L(d_0) + 10k\log_{10}(\frac{d}{d_0}),\ d \geq d_0 \quad (9)$$

In Eq. (9), $P_L(d)$ indicate the path loss between the CMs and CH over distance d, and k is path loss exponent where $k = 3$. In free space, $P_L(d_0)$ can be defined as $P_L(d_0) = 20\log_{10}(\frac{4\pi d_0}{\lambda})$, where d_0 is a received-power reference point and usually $d_0 = 1\ m$, λ is wavelength in meters. We substitute Eq. (8) into the Eq. (9) and rearrange Eq. (9) as:

$$\overline{P_L(d)} = 20\log_{10}(\frac{4\pi}{\lambda}) + 10k\log_{10}(\sqrt{\frac{A}{4M_t p}}),\ d_0 = 1 \quad (10)$$

Due to substituting the logical cluster size into the path loss propagation model, the formula describes the impact of CR, p, on $\overline{P_L(d)}$ which means average path loss level in each cluster. After that we develop a threshold value for guaranteeing an expected PRR and minimizing retransmission.

We assume P_i is a Bernoulli random value, where, if the packet is received $P_i = 1$, otherwise $P_i = 0$. Then, because of P_i is independent identically distributed random value, by the weak law of large numbers PRR can be approximated by P_S which is the probability of successfully receiving a packet and calculated by the following equation [6].

$$P_S = (1 - P_e)^{8F} \quad (11)$$

Where, F is a frame size in bytes, and P_e is probability of bit error which mainly depends on the modulation scheme. In this paper, we assume sensor nodes equipped with radio transceivers provide FSK modulation scheme to transmit signal, then P_e is given by: [6].

$$P_e = \frac{1}{2}e^{-\frac{\alpha}{2}} \quad (12)$$

In Eq. (12), $\alpha = \frac{E_b}{N_0}$ which is energy per bit (E_b) to noise power spectral density (N_0) ratio. In order to develop relation between p P_S, α need to be converted to SNR (Signal to Noise Ratio) by equation $SNR = \frac{E_b R}{N_0 B_N}$. Where, R is data rate in bits, and B_N is noise bandwidth. We assume $R = 19.2\ kbps$ and $B_N = 30\ kHz$. Hence, P_S is defined as:

$$P_S = (1 - \frac{1}{2}e^{-\frac{B_N}{2R}SNR})^{8F} = (1 - \frac{1}{2}e^{-\frac{SNR}{1.28}})^{8F} \quad (13)$$

The SNR can be transformed into form of $SNR = r_{ss} - N_{floor}$. Where, r_{ss} is the receive sensitivity for correctly receive data packet in CHs, and $N_{floor} = -115\ dBm$ which means the system noise floor. Then Eq. (13) is converted into following formula.

Table 1: Parameter definitions

Parameters	Definition
R	$19.2\ kbps$
B_N	$30\ kHz$
N_{floor}	$-115\ dBm$
P_t	$0\ dBm$
$d_0,\ \lambda$	$1,\ 0.125\ m$
F	$50\ bytes$

$$P_S = (1 - \frac{1}{2}e^{-\frac{r_{ss}-N_{floor}}{1.28}})^{8F} \quad (14)$$

Let r_{ss} be a variable in Eq. (14) and drive inverse function as Eq. (15), then we can get the threshold value of r_{ss}^{th} which can guarantee the expected packet receive probability P_{expect}.

$$r_{ss}^{th} = N_{floor} + 10\log_{10}(-1.28\ln(2(1 - P_{expect}^{\frac{1}{8F}}))) \quad (15)$$

Given a transmitting power P_t, r_{ss}^{th} can be expressed as $\underline{r_{ss}^{th} = P_t - P_L}$ and according to previous analysis results of $\overline{P_L(d)}$, $r_{ss}^{th} = P_t - \overline{P_L(d)}$, which leads to:

$$p = \frac{A}{4M * 10^{(\frac{P_t - N_{floor} - 20\log_{10}(\frac{4\pi}{\lambda}) - 10\log_{10}(-1.28\ln(2(1-P_{expect}^{\frac{1}{8F}})))}{5k})}} \quad (16)$$

Finally, substituting the parameters list in Table 1 into Eq. (16), we figure out an ill-advised CR selection leads to high level of packet loss in a cluster. That is the reason of why an optimal CR can reduce energy consumption by guaranteeing PRR in the cluster scheme. According to Eq. (17) an optimal CR can be obtained which can guarantee the expect packet receive probability P_{expect}.

$$p = \frac{A}{4M_t * 10^{(\frac{74.96 - 10\log_{10}(-1.28\ln(2(1-P_{expect}^{0.0025})))}{15})}} \quad (17)$$

In the next section, we will determine an optimal CR based on Eq. (17), and compare the mathematical analysis with simulation. Comparison with LEACH which set a static CR to 5% shows the optimal CR is powerfully guarantee PRR.

4. SIMULATION RESULTS

In the simulation, our network is deployed in a geographical area $1000\ m * 1000\ m$. We assigned the number of sensor nodes as 750 and they are randomly deployed in the area. The operating frequency is $2.4\ GHz$, the power available among all sensor nodes is $0\ dBm$, and we neglect shadow fading and multi path fading in the simulation. In order to guarantee 90% PRR in our simulation environment, we calculated the optimal CR based on Eq. (17) and the initial CR set to 5% in LEACH. The number of packets sanded by CMs is in range of 100 to 10000 , and the frame size is 50 *bytes*. More detail simulation parameters are shown in Table 1.

Fig. 2, evaluates the impact of varying number of CR on the average path loss between CH and CMs in a cluster. The

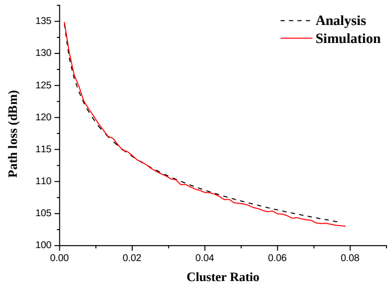

Figure 2: Comparison of average path loss in a cluster

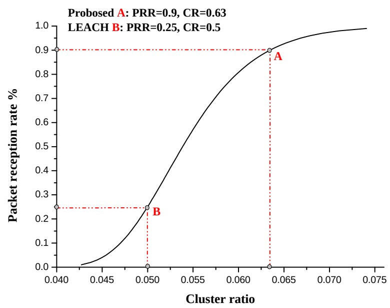

Figure 3: Analysis on relation between CR and PRR

Curves in Fig. 2 indicate that increased the number of CR leads to exponential decrease of path loss because of a higher SNR can be obtained. In addition, it shows the graph of the numerical results based on Eq. (10) is very similar to the graph from the simulations, and that means our developed formula can reliably express the relation between CR and path loss.

Fig. 3 shows the CR impact on the PRR in WSN. It is observed that the initial CR set to 5% in LEACH just obtain 0.25 PRR which means serious data packet loss will be occurred and reduce life time of the network. On the other hand, the optimal CR can be selected as 6.3% which can guarantee 90% PRR.

In Fig. 4, we analyze convergence of the PRR in CR= 0.5 and CR= 0.63 situation by simulation. With increase of the number of transmitted packets from CMs to CH, we find that each of curve converge into a determined value which equal to the value showed in Fig. 2. It is indicates that our proposed formulas are promised and the selected number of cluster ratio is effectively guarantee the PRR in cluster based WSN.

5. CONCLUSIONS

In this paper we focus on developing the optimal CR to guarantee PRR. As we investigate clustering algorithms in WSN, we find the relation between the CR and the path loss in a cluster. We mathematically proof it and develop the threshold value to provide promising channel. Finally, in order to reduce energy consumption by minimizing the packet loss, the optimal CR is developed, and the simulation results show it is effectively guarantee the PRR than the

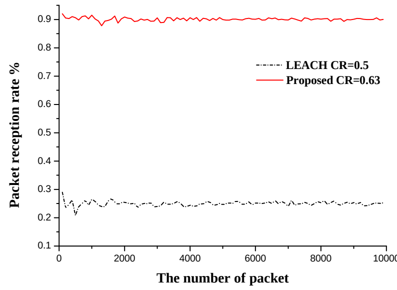

Figure 4: Guaranteed PRR in simulation results

static CR proposed by LEACH.

6. ACKNOWLEDGMENTS

This work was supported by the MKE(The Ministry of Knowledge Economy), Korea, under the ITRC(Information Technology Research Center) support program supervised by the NIPA(National IT Industry Promotion Agency) (NIPA-2011-(C1090-1121-0003)) and by Mid-career Researcher Program through NRF grant funded by the MEST (No. 2011-0015744).

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