Energy Efficient Fractional Coverage Schemes for Low Cost Wireless Sensor Networks

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Abstract

An effective approach for energy conservation in wireless sensor networks is scheduling sleep intervals for extraneous nodes, while the remaining nodes stay active to provide continuous service. Depending on different types of applications, the network lifetime may be much more critical than covering the entire monitored area at every data reporting round. This paper presents a competition based distributed scheme called FCS to address the fractional coverage problem in wireless sensor networks with tiny, low-cost sensors. Through localized, energy-aware competition, the proposed scheme achieves the desired fractional coverage with a minimum number of active sensors. By taking account of both residual battery energy and recent reporting latency, an enhanced version of FCS which uses a novel competition metric to constrain the maximum reporting latency throughout the network is also proposed. These two schemes also contain the desirable property that it can be extended easily to handle the more general k-coverage problem.

Keyword— energy awareness, fractional coverage problem, reporting latency, wireless sensor network.

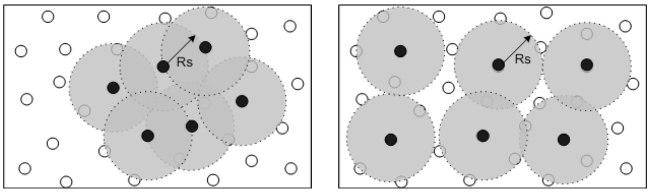
Area— sensor network, network coverage.

1 Introduction

Continued advances in MEMS and wireless communication technologies have enabled the deployment of large scale wireless sensor networks (WSNs) [1]. Such sensor networks can be characterized by high node density and highly limited resources such as battery power, computational capability and storage space, which distinguishes themselves from traditional ad hoc sensor networks. Since the battery in each sensor is power limited and usually not renewable, energy conservation is important to extend the lifetime of both the individual node and the network. Recent research [2–8] has found that significant energy savings can be achieved by dynamic management of node duty cycles in sensor networks with high node density. In this approach, some nodes are scheduled to sleep (or enter a power saving mode) while the remaining active nodes continue to provide service. A fundamental problem is how to minimize the number of nodes that remain active and maintain the network function at the same time.

Most of the existing protocols [3–6] in the literature are solutions for complete coverage problem, i.e., covering the entire sense field. However, achieving complete coverage is usually very costly and energy wasting, and fractional coverage is a promising and energy efficient approach in some applications such as [1, 9]. By selecting only a subset of the nodes to be active at a given time, it is possible to achieve a suitable trade-off between energy-efficiency and the desired level of monitoring accuracy. Moreover, unlike many existing work in sensor coverage, we do not assume that the sensors are location aware, i.e. equipped with GPS or similar capabilities. Thus our network model is that of a large, dense network of low cost sensors, with only selected subsets activated in any single data reporting cycle to conserve energy. Our work is motivated in part by the pioneering work by W. Choi et al., who propose strategies to deal with the fractional coverage problem for data gathering in WSNs [8]. They proposed a pure random strategy to produce the desired minimum number of working sensors in each round and make a few improvements regarding the reporting latency for time-sensitive applications.

In this paper, we use a localized energy-aware competition approach in developing our Fractional Coverage Scheme (FCS). To achieve a better balance between energy efficiency and reporting latency, a modified version of FCS called Enhanced FCS (EN-FCS) is proposed as well. This protocol uses a novel competition metric to constrain the maximum reporting latency throughout the network. Furthermore, we investigate the properties of the active sensor topology (AST) produced by FCS/EN-FCS and give the op-



(a) poor distribution of AST (b) fair distribution of AST

Figure 1. Distributions of AST of the network.

timized competing range analytically. Simulation results indicate the performance of FCS is better than comparable algorithms, while EN-FCS achieves significant improvement in terms of the maximum reporting latency.

The remainder of this paper is organized as follows. The preliminary problem of this work is described and analyzed in Section 2. Section 3 presents the details of our basic algorithm (FCS) for solving the fractional coverage problem as well as an enhanced version called EN-FCS for reducing the reporting latency. Section 4 contains an analysis of the properties of the two algorithms, followed by evaluation of their performance using simulation experiments in Section 5. Finally, the paper concludes with a summary of our contributions as well as future work in Section 6.

2 Preliminary Problem

In this paper we assume that a dense sensor network has been deployed. Each round only a few sensors are selected and activated to report the peripheral sensing data to a remote base station (BS). To simplify the problem, we make a few reasonable assumptions about the network model as follows. There are N sensors dispersed uniformly over the network in a two-dimensional geographic area A, forming a network and the communication between them is symmetric. Each sensor is equipped with a sensing component which can collect information within a R_s circular area. However, sensors are not located by any specific coordination system because such mechanisms may not be available or practical in building low-cost and low-power sensors with small form factor. Sensors can use power control to vary the amount of transmit power depending on the distance to the receiver [10], in order to conserve power and attain the desired transmission range at the same time. Coverage requirement is depend on different applications and denoted by η.

In [8], W. Choi et al. present a detailed analysis on the determination of $min\{|S_a|\}$ based on a pure stochastic assumption, where S_a stands for the set of active sensors. For η fractional coverage problem, the desired minimum number of active sensors is

$$min\{|S_a|\} = \lceil \frac{log(1-\eta)}{log(\frac{A+4\sqrt{A}R_s}{A+4\sqrt{A}R_s+\pi R_s^2})} \rceil. \quad (1)$$

However, a purely random scheme is not an efficient approach for coverage problem in wireless sensor networks. As shown in Fig. 1-(a), poor distribution leads to a lot of overlap among the covered regions, which severely impacts the coverage of entire sensing area, and potentially increases the number of necessary selected active sensors. Ideally the sensors should be evenly distributed, with little overlap among regions, as shown in Fig. 1-(b). Hence the desired minimum number of necessary active sensors in ideal distribution case, rather than in pure stochastic case, is

$$min\{|S_a|\} = \frac{\eta A}{\pi R_s^2}. \quad (2)$$

3 Overview of FCS and EN-FCS

FCS is a competing-based distributed algorithm, where only a subset of the installed nodes are chosen by localized competition to sense and report data each round. We rotate the active roles periodically over the network to guarantee that no sensor is easy exhausted, which may result in “monitoring hole”. By optimizing competing range and energy-aware competition, FCS achieves the QoS of specific applications, i.e., desired mean coverage fraction, while maintaining extended network lifetime. In this paper, we mainly focus on how to schedule sensors to work over the entire network. Our strategy is purposely simple in order to minimize processing and communications overhead. In the network deployment phase, the base station broadcasts a “hello” message to all nodes at a certain power level. Subsequently, each node n_i exchanges “hello” message with its neighbors and computes the surrounding node density ρ_i for later use. Finally, each node enters into the periodical data reporting phase and takes over the information reporting task in individual active round. The details of FCS are given in the following subsection.

3.1 Fractional Coverage Scheme (FCS)

Active sensor selection is the most critical part in coverage problem of wireless sensor networks. There are two phases: *advocation phase* and *competition phase* in our FCS algorithm. In *advocation phase*, several pioneer nodes are selected to compete for active sensors. Each node becomes a pioneer with the probability T_i, which is a function of surrounding node density ρ_i.

$$f(\rho_i) = \begin{cases} 1, & \rho_i < c \\ \frac{c}{\rho_i}, & \rho_i \geq c \end{cases}, \quad (3)$$

where c is the ideal node density of pioneer sensors, which is determined by each specific application. Other nodes keep sleeping till the next round. In this phase, each pioneer advocates the willingness within its competing range R_c and as well receives other pioneers' advocating messages `COMPETE_MSG`s. In the next *competition phase*, residual battery energy, E_r, is introduced as the competing metric. Each pioneer sensor waits for the decision of all the neighboring competitors with more energy. Pioneer sensor with more residual energy wins the competition with a high probability. Following are three message triggered procedures:

on receiving `COMPETE_MSG`: On receiving a `COMPETE_MSG` from a neighboring competing node n_i, node n_j checks if it has received all the neighboring `COMPETE_MSG`s. Once n_j is the most powerful node of the competing neighbor set S_c, i.e., $n_j.E_r > n_i.E_r, \forall n_i \in n_j.S_c$, it broadcasts `WIN_MSG` within the competing range to advocate its succuss and exits this competition phase.

on receiving `WIN_MSG`: Receiving `WIN_MSG` means that node n_j loses the competition. It advertises `GIVE_UP_MSG` within the competing range and exits the competition phase.

on receiving `GIVE_UP_MSG`: On receiving a `GIVE_UP_MSG` from node n_i, node n_j checks if it is the most powerful node comparing to the remaining competing neighbors. That is to say, if $n_j.E_r > n_k.E_r, \forall n_k \in n_j.S_c$, where $n_j.S_c = n_j.S_c - \{n_i\}$, n_j wins the competition by broadcasting `WIN_MSG` within the competing range and this competition phase ends.

In order to decide whether it is going to be an active sensor or an ordinary one, each pioneer sensor waits for the decision of all the neighboring competitors with more residual energy ($weight$, in EN-FCS). This "waiting time" of each node can be defined as a function of the distance of a node from one of the initial nodes. Clearly, this "blocking distance" (D_b) [11] depends on the current topology of energy distribution rather than on N, the number of the nodes in the network. Hence the competing round is asymptotic to $O(D_b)$ rather than $O(N)$.

3.2 Enhanced Fractional Coverage Scheme (EN-FCS)

In time-sensitive applications employing fractional coverage of wireless sensor networks, the maximum reporting latency is also a key performance metric besides guaranteed coverage ratio. For instance, users may impose a maximum latency in reporting sensing data of a given area. As FCS only focuses on the energy issue and coverage fraction, we develop an enhanced version of FCS called EN-FCS, to constrain the reporting latency over the sense field.

Fig. 2 shows why FCS does not meet latency requirements satisfactorily. Although FCS achieves the desired coverage ratio in these two sequential reporting rounds (Fig. 2-(a) and 2-(b)), there are a few regions not covered in both rounds. On the other hand, the distribution shown in Fig. 2-(c) is a desirable AST distribution for the second reporting round, as most of sense field is covered in these two rounds.

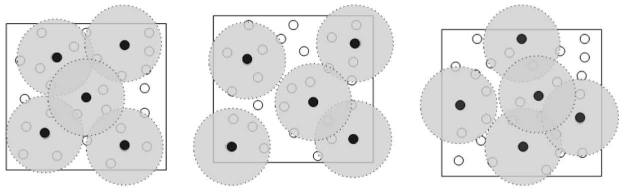

(a) one arbitrary round
(b) The subsequent round in FCS
(c) The subsequent round in EN-FCS

Figure 2. Two sequential distributions of AST of the network.

We can observe from Fig. 2 that sensors residing in the region which have not been covered recently should have a much larger probability to win the competition. EN-FCS achieves the desired effect by substituting E_r in FCS with a weighting factor which takes into consideration both the residual energy of the nodes as well as the latency. In addition, a procedure is introduced to deal with the weight updating. More formally, we define the decision factor during the competition in EN-FCS as follows:

$$g(l_r, E_r) = l_r^{\alpha} \times E_r, \tag{4}$$

where α is a weight factor.

Unlike the original FCS, competition winners broadcast `ACTIVE_MSG`s within R_i radio range to inform neighboring sensors of the coverage circumstance. Any informed sensor resets its l_r and gives a larger chance to the sensor that has not received any `ACTIVE_MSG`, as there is a high probability that it may be covering a much larger area which is experiencing even longer reporting latency. The latency counter l_r of each sensor increases every round unless it receives the coverage information (including itself being an active sensor) in this period.

4 Theoretical Analysis of AST

In this section, the properties of active sensor topology (AST) generated by the FCS and EN-FCS algorithms are examined analytically.

Lemma 1. *Let $d(x, y)$ denote the distance between sensor x and y. We have $d(x, y) \geq R_c$ ($\forall x, y \in S_a$), using the FCS algorithm.*

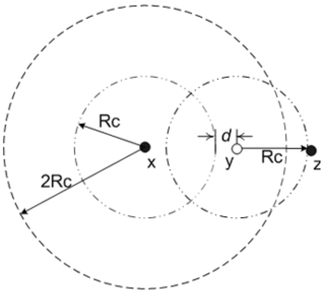


Figure 3. Largest distance between two neighboring active sensors.

Proof. Based on the competition strategy in FCS, we can easily deduce that $d(x, y) \geq R_c, \forall x, y \in S_a$ over the entire network. ☐

Lemma 2. *For any given active sensor x, there exists at least one neighboring active sensor within $2R_c$.*

Proof. As shown in Fig. 3, we assume node y is an arbitrary sleeping node residing in the area between two concentric circles with radius R_c and $2R_c$ centered at node x. According to the competition mechanism of the FCS, there must exist at least one active sensor within the circle center at node y with radius R_c, and none of any other active sensor within the dotted circular area centered at x. Let d denote the distance between y and x's R_c circular area. It can bee seen in Fig. 3 that node z is the farthest possible active sensor within the R_c circle of node y and is $2Rc + d$ distance away from node x. Thus the distance between node x and the possible farthest neighboring active sensor is $\min\{2Rc+d_y\}$. Inspired by the similar theorem in [12], we have $\lim_{N\to\infty} d = 0$. Therefor, we conclude that there exists at least one neighboring active sensor within any active sensor's $2R_c$ circular range in a dense WSNs. ☐

Lemma 3. *In our sensor network model, we consider two active sensors are adjacent if the distance between them is no larger than $2R_c$. Then the expected distance between any two adjacent active sensors is $\frac{14}{9}R_c$, where R_c is the competing range.*

Proof. Observing Lemma 1 and 2, we find the distance between any adjacent active sensors is between R_c and $2R_c$. Since the residual energy distributed over the network is arbitrary, the probability of l distance, $Prob(l)$ is given as

$$Prob(l) = \frac{2\pi l}{\pi(2R_c)^2 - \pi(R_c)^2} = \frac{2}{3}\frac{l}{R_c^2}. \tag{5}$$

Parameter	Fixed Value	Varied Value
N	$300, 500, 700$	$200 \sim 800$
η	$0.4, 0.6, 0.8$	$0.3 \sim 0.9$
c	0.025	
R_s	10	
R_c	$\frac{9}{7\sqrt{\eta}}R_s$	
R_i	$\sqrt{3}R_s$	
α	3	
A	100×100	

Table 1. Parameters of simulations

Thus the expected distance is

$$E(l) = \int_{R_c}^{2R_c} l \times \frac{2}{3}\frac{l}{R_c^2}\mathrm{d}l = \frac{14}{9}R_c. \tag{6}$$

☐

Corollary 1. *The optimized competing range for the fractional coverage problem is $\frac{9}{7\sqrt{\eta}}R_s$.*

Proof. Observing Lemma 3 and Eq. 2, for the η fractional coverage problem, we have $\frac{A}{\pi(\frac{7}{9}R_c)^2} = \frac{\eta A}{\pi R_s^2}$. Thus the optimized competing range is $R_c = \frac{9}{7\sqrt{\eta}}R_s$.

Based on the theorem proposed in Section 2, we find FCS can be extended to resolve more general k-coverage problem ($k > 0$), where the optimal competing range is $\frac{9}{7\sqrt{k}}R_s$ ☐

Corollary 2. *EN-FCS holds the same statistical characteristics in the distribution of active sensors as FCS.*

Proof. Substituting E_r with $weight$, we can easily conclude that the distribution of active sensors in EN-FCS is the same as in FCS. ☐

5 Performance Evaluation

In this section, we evaluate the performance of FCS and EN-FCS in handling data gathering and reporting for user applications. Our simulation experiments are based on the model and parameters used in the well-known LEACH protocol [13]. To the best of our knowledge, the only published work in the area of fractional coverage in sensor networks is the pioneering paper by W. Choi et al. [8], and we will be using an idealized version of their pure stochastic based (PSB) protocol as the benchmark in our simulation experiments. PSB is based on an analytical model in W. Choi et al.'s work and demonstrated in their paper to generate result that always outperform the three protocols in terms of coverage. Using PSB simplifies the comparison since we do not need to deal with the all three protocols separately in our experiments.

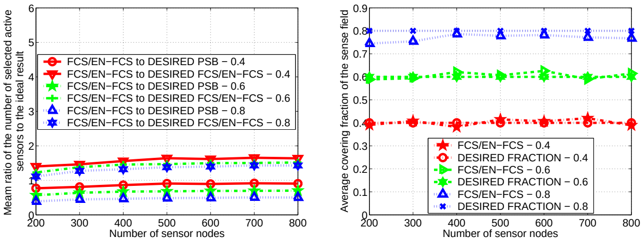
We note here that our notion of latency is different from that of W. Choi et al. In their approach, the maximum reporting latency in terms of sensor node. At every cycle C, each sensor elects itself as a reporter by drawing a round randomly with θ reporting rounds of C, thus the reporting latency of each sensor in N-DRS ranges from $\theta \times \delta t$ to $2\theta \times \delta t$. Furthermore, the reporting latency is enhanced to $\theta \times \delta t$ in F-DRS. However, we consider "area reporting latency ", instead of "reporting latency of sensor node" is more meaningful in some applications such as [9], since reduction in the latency for a report area is more suitable in such applications than individual sensors. Consequently, latency in all our experiments refer to area reporting latency. The formal definition of area reporting latency is as follows.

$$\max_{(x,y)\in A}\{\max_{T_{i-1}<T_i<\mathit{lifetime}}\{T_i(x,y)-T_{i-1}(x,y)\}\}, \qquad (7)$$

where $T_i(x,y)$ denotes the time of i_{th} reporting round occurred on the area point (x,y).

In our experiments, we ignore signal collision and interference in the wireless channel for simplicity. Several system parameters are listed in Tab. 1. Unless otherwise specified, each simulation result shown below is the average of 100 independent experiments where each experiment uses a different, randomly generated uniform topology of sensors.

As we mentioned earlier in Section 2, the critical issue of fractional coverage is how to select the minimum number of active sensors, while achieving the desired coverage fraction . Thus we evaluate the performance of FCS and EN-FCS based on the following metrics: the *mean number of selected active sensors* ($\overline{|S_a|}$) and the *average covering fraction* ($\overline{\eta}$). Our analysis in Section 4 indicated that FCS and EN-FCS has the same behavior in terms of coverage; this is confirmed by Fig. 4 and 5.

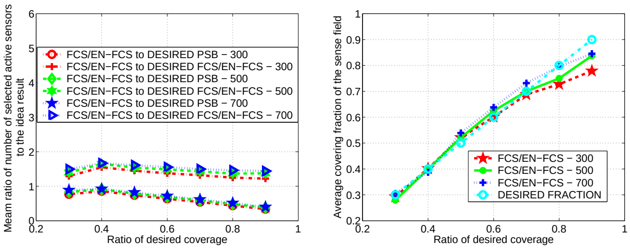


(a) Evaluation of $\overline{|S_a|}$

(b) Evaluation of $\overline{\eta}$

Figure 4. Effect of number of sensor nodes on (a) $\overline{|S_a|}$, and (c) $\overline{\eta}$.

First we examine the impact of node density on the performance of FCS/EN-FCS with different coverage requirements ($\eta = 0.4, 0.6$ and 0.8). As N varies from 200 to 800, Fig. 4 shows the relation between N and the coverage performance, i.e., $\overline{|S_a|}$ and $\overline{\eta}$. We find the desired number of selected active sensors is independent of the node density. Because the competing mechanism produces a fair distribution of active sensors, FCS/EN-FCS outperforms the ideal case of PSB algorithm significantly. The impact of the edge effect (ignored in analytical results) is apparent in the simulation results, and we find the FCS/EN-FCS protocol selects some more active sensors than predicted by the analytical results, as shown in Fig. 4-(a). In Fig. 4-(b), the actual coverage quality of FCS/EN-FCS deviates from the predicated value when η is 0.8. We will give a detailed explanation in the next paragraph.



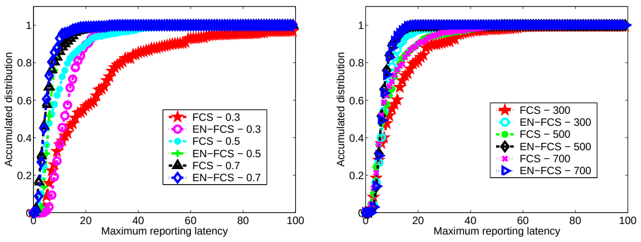
(a) Evaluation of $\overline{|S_a|}$

(b) Evaluation of $\overline{\eta}$

Figure 5. Impact of η for different number of sensor nodes: (a) $\overline{|S_a|}$, and (b) $\overline{\eta}$.

Fig. 5 shows the impact of η on the performance of FCS/EN-FCS in different network density ($N = 300, 500$ and 700). According to the analytical results proposed in Section 2, FCS/EN-FCS should exhibit a smaller increase in the number of active sensors with increasing coverage area when compared to PSB. This prediction is confirmed by the simulation results shown Fig. 5-(a), particularly for large η. We note however that in Fig. 5-(b), while FCS/EN-FCS behaves as predicted by the analytical results, there is a small degradation in its performance when η is large. As we mentioned earlier, FCS/EN-FCS usually selects more active sensors than predicted by our analytical model due to the edge effect. Consequently the real coverage ratio tends to be somewhat larger than the desired η, as part of the coverage area of active sensors residing near the edge of the sense field will be wasted. Since the number of active sensors near the marginal area grows as $|S_a|$ increases, actual results for η will be lower than the predicted values, as the number of sensor suffering from this effect increases. This explains the small degradation in actual results compared to predicted results in Fig. 5-(b).

Fig. 6 compares the performance of FCS and EN-FCS in terms of maximum reporting latency. For an application



(a) Varied η (b) Varied N

Figure 6. Effect of (a) varied η, and (b) varied N on maximum reporting latency for FCP and EN-FCP.

requiring coverage ratio of η, the desired maximum reporting latency is $\frac{1}{\eta}$. Thus we find EN-FCS performs even better when η is small as shown in Fig. 6-(a). Additionally, Fig. 6-(b) shows that the maximum reporting latency in EN-FCS is independent of the network density, especially in large scale sensor networks. Note that this substantial improvement is achieved at the expense of just a small increase in the message overhead ($|S_a|$) compared to FCS. Incidentally, we have also implemented an alternative EN-FCS protocol by substituting l_r with frequency of node selection (f_a) to constrain the area reporting latency. However, although the use of (f_a) may seem intuitively appealing, we observed that the reporting latency does not improve significantly in this alternative protocol. This is because if (f_a) is used, two adjacent sensors may be selected as active nodes in two subsequent rounds respectively. Therefore, we concluded that l_r is more meaningful than f_a in reducing area reporting latency and this is the approach used in all our experiments.

6 Conclusion and Future Work

In this paper, we presented a novel energy-aware, competing-based, distributed algorithm called FCS for solving the fractional coverage problem in wireless sensor networks. Through localized competition in optimized range, FCS achieves the desired coverage fraction with a minimum number of active sensors. We then introduced an enhanced version of FCS which uses a novel competing metric to investigate the tradeoff between energy awareness and time sensitiveness. Our simulation results show that both FCS and EN-FCS behave almost the same as analytical results and significantly outperform similar algorithms. Most of our contributions here are focused on the fractional coverage problem. However, we note that our approach can be easily extended by appropriately adjusting the competing range R_c to handle the k-coverage (i.e., $\eta \geq 1$) problem as well. In large scale sensor networks, multi-hop communication is a mainstream technique for energy saving, and our goal is to design an integrated connectivity and coverage protocol based on FCS/EN-FCS which is independent of the communication range in the future work.

Acknowledgements

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