Coverage Enhancing Algorithm based on Numerical Analysis and Greedy Iteration in Directional WSN

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Abstract. Aiming at the high complexity and low coverage ratio of existing coverage enhancing algorithms in directional wireless sensor network, a coverage enhancing algorithm based on numerical analysis and greedy iteration is proposed. The proposed algorithm adjusts the sensor direction by way of greedy iteration, until all sensor directions reach local optimum. Meanwhile, in the process of greedy iteration, greedy iteration is used to simplify the area calculation to reach the reduction of the complexity of the proposed algorithm. The simulation demonstrates that the proposed algorithm is well convergent with high coverage rate and medium execution time.

Introduction

WSN (Wireless Sensor Network) is widely used in many fields as a monitoring network[1-3]. Sensors in the WSN are divided into directional sensors and omni-directional sensors according to the shape of sensing field of the sensor [4,5]. Wherein, the directional sensor refers that the sensing perspective of the sensor is limited, the sensing field only contains a fan-shaped area, while WSN composed of directional sensors is also called directional WSN [6]. Coverage control technology is important means to improve WSN coverage rate [7]. Coverage enhancement algorithm based on greedy algorithm and probability enhancement is proposed in literature [8] and literature [9] according to fixed adjustable model of sensing direction. The sensing direction of each sensor can be adjusted according to priority order in the algorithm. In addition, the adjusting frequency of each sensor sensing direction can not be higher than 1. Greedy algorithm is used for increasing the complexity of coverage enhancement algorithm.

Existing coverage enhancement algorithm still has some problems of high complexity, irrational coverage rate, etc. through the above analysis. In the paper, Coverage Enhancement Algorithm based on Numerical Analysis and Greedy Iteration (CENAGI for sort) is proposed in the paper aiming at these problems. CENAGI algorithm can realize higher coverage rate with the least complexity.

Coverage enhancement algorithm based on numerical analysis and greedy iteration

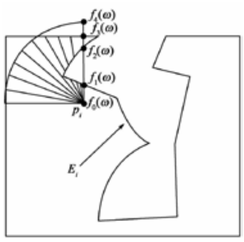
It is assumed that if the to-be-adjusted sensor is i, the sensing directions before i adjustment and after i adjustment are respectively $a_i^{'}$ and a_i^{*} in the iteration process, if $\phi\left(r,\theta,p_j,a_j\right)$ and $\phi\left(r,\theta,p_j,a_i^{'}\right)$ or $\phi\left(r,\theta,p_j,a_i^{*}\right)$ has overlapped region aiming at $\forall j \in N_i$, the neighboring sensor $\forall j \in N_i$ state and priority should be updated only, and next iteration can be started.

In step (13) of CENAGI algorithm, constant d ($d \geq 0$) refers to iteration number control factor, d value is smaller, coverage rate many be improved more. However, d value is smaller, iteration number is more, and algorithm spending time is longer.

Firstly, the solution of $\varphi_i\left(a_1^{'},a_2^{'},\cdots,a_n^{'}\right)$ is analyzed, namely $Area\left(R\cap\left(\varphi\left(\gamma,\theta,p_i,a^{'}_i\right)-\phi\left(\gamma,\theta,p_i,a^{'}_i\right)\cap\left(\bigcup_{j\in N_i}\phi\left(\gamma,\theta,p_j,a_j\right)\right)\right)\right)$ is calculated. One edge sequence can be used for representing 2D target region as R and $\phi\left(r,\theta,p_i,a'_i\right)$ as shown in Figure 3.1. Figure 3.1 shows that sensor i sensing region is represented by $\left\langle p_i q_0, q_o\hat{q}_1, q_1 p_i\right\rangle$. In the formula, $\overset{\wedge}{q_o q_1}$ is arc between q_o and q_1. Then, computation geometry in literature [64] is used for obtaining intersection and union area of these regions, thereby obtaining $\varphi_i\left(a'_1,a'_2,\cdots,a'_n\right)$ value. Since there are a total of $O\left(\delta^2\right)$ edges in region $R\cap\left(\varphi\left(\gamma,\theta,p_i,a'_i\right)-\phi\left(\gamma,\theta,p_i,a'_i\right)\cap\left(\bigcup_{j\in N_i}\phi\left(\gamma,\theta,p_j,a_j\right)\right)\right)$, computation complexity of $\varphi_i\left(a'_1,a'_2,\cdots,a'_n\right)$ is $O\left(\delta^3\right)$.

Search of a_i value of $\varphi_i\left(a'_1,a'_2,\cdots,a_i,\cdots,a'_n\right)$ during the maximum value can be divided into four steps:

(1) Sensor i private coverage region can be written into $\left[R-\bigcup_{j\in N_i}\phi\left(\gamma,\theta,p_j,a'_j\right)\right]\cap\varphi\left(\gamma,\theta,p_i,a'_i\right)$, therefore $\left[R-\bigcup_{j\in N_i}\phi\left(\gamma,\theta,p_j,a'_j\right)\right]$ can be firstly calculated, and $E_i=R-\bigcup_{j\in N_i}\phi\left(\gamma,\theta,p_j,a'_j\right)$ is set. E_i must be irregular shape formed by the line segment and arc as shown in Figure 2.



Figurec 1. E_i shape

(2) Vector $v_i(w)$ length is set as r, and the starting point is p_i. In addition, w is the inclined angle thereof with X axis. $f_e(w)=\|v_i(w)$ and e intersection $\|P_i$ is set aiming at $\forall e\in E_i$. If e is an arc , and the focus quantity between $v_i(w)$ and e is 2, then functions $f_e(w)$ and $f'_e(w)$ are defined. Meanwhile, F_i is set as combination of $f_e(w)$ and $f'_e(w)$, namely $F_i=\left\{f_e(w),f'_e(w)\middle|e\in E_i\right\}$.

(3) It is assumed that the center is p_i, and the radius is r. In addition, the area of unit angle of the fan shape with inclined angle w with X axis in E_i is represented by $g_i(w)=d\varphi_i\left(a'_1,a'_2,\cdots,w,\cdots,a'_n\right)/d\theta$, then

$$\varphi_i\left(a'_1,a'_2,\cdots,a_i,\cdots,a'_n\right)=\int_{a_i-\theta/2}^{a_i+\theta/2}g_i(w)dw \tag{2}$$

$g_i(w)$ computing method is shown as follows: firstly, functions with definitions on w in F_i should be sequenced according to gradual decrease order. $f_1(w)$, $f_2(w)$, $\cdots$, $f_m(w)$ is assumed, and $f_0(w)=0$, $f_{m+1}(w)=r$ as shown in Figure 2. When p_i is located within region E_i, $g_i(w)=\sum_{i=0}^{\lfloor(m+1)/2\rfloor}\left[f_{2i}^2(w)-f_{2i-1}^2(w)\right]/2$.

(4) Meanwhile, numerical analysis is applied for discovering a_i value of $\varphi_i\left(a'_1,a'_2,\cdots,a_i,\cdots,a'_n\right)$ during the maximum value. Firstly, the circle center is located in p_i. The circle with radius of r is equally divided into b fan shapes. Then, the inclined angle between the

right edge of the kth fan shape and X axis is $w_k = 2\pi k / b$, $0 \le k < b$. Then, the area of all fan shapes in the region E_i is calculated, If b is larger, the fan shape area is closer to $2\pi g_i(w_k)/b$. $c = \lfloor b\theta / (4\pi) \rfloor$ is set, the fan-shaped region quantity within sensor i is $2c$, then:

$$\begin{aligned} &\varphi_i\left(a_1^{'}, a_2^{'}, \cdots, w_0, \cdots, a_n^{'}\right) \approx 2\pi\left[\sum_{j=0}^{c-1} g_j(w_j) + \sum_{j=b-c}^{b-1} g_i(w_j)\right]/b \\ &\varphi_i\left(a_1^{'}, a_2^{'}, \cdots, w_k, \cdots, a_n^{'}\right) \approx \varphi_i\left(a_1^{'}, a_2^{'}, \cdots, w_{k-1}, \cdots, a_n^{'}\right) + 2\pi\left[g_i(w_{(k+c-1)\%b}) - g_i(w_{(k-c-1)\%b})\right] \end{aligned} \quad (3)$$

The value of $\varphi_i\left(a_1^{'}, a_2^{'}, \cdots, a_i, \cdots, a_n^{'}\right)$ in $2\pi k / b$ can be calculated according to formula (3) on the basis of recursion mode, $0 \le k < b$, $0 \le a_i < 2\pi$. When b is larger, the discovered $2\pi k^{'} / b$ is the approximate value for searching local optimum sensing direction. Since E_i edge quantity is $O(\delta^2)$, the time complexity of E_i is calculated as $O(\delta^3)$. Meanwhile, the complexity for calculating $\varphi_i\left(a_1^{'}, a_2^{'}, \cdots, w_k, \cdots, a_n^{'}\right)$ is $O(b\delta^2 \log \delta)$. Therefore, the computing complexity of local optimum sensing direction is obtained as $O(b\delta^2 \log \delta + \delta^3)$.

Simulation analysis

In the paper, CENAGI algorithm performance is evaluated from three aspects of convergence, coverage and execution time. Meanwhile, CENAGI algorithm is compared with PFCEA algorithm in literature [57] and PGreedy algorithm in literature [59], thereby better evaluating the efficiency of CENAGI algorithm. Parameters are $d = 0$ and $b = 500$ in CENAGI algorithm on the basis of giving equal attention to algorithm accuracy and execution time. In addition, 2D target region R is set as a square region, the region area is $l*l$, n sensors in WSN are randomly distributed in target region. The sensor density within R is ρ.

Convergence. The set simulation parameters are set as follows in order to verify the convergence of CENAGI algorithm: $r = 10$ m, $\theta = \pi/2$, $\rho = 0.016m^{-2}$, $(l,\ n)$ is respectively (50m,40), (100m,160), (150m,360) and (200m,640). In addition, each simulation is repeated for 100 times. Finally, the average value of 100 simulation results is obtained. Figure 3 shows the change condition of CENAGI algorithm coverage with number of iterations. Figure 3 shows that CENAGI algorithm iteration number is also increased with target region increase. The average value of CENAGI algorithm iteration number is 97 times during $l = 200m$. Meanwhile, it can be observed that after iteration number reaches 20, CENAGI algorithm coverage rate can basically be more than 95%.

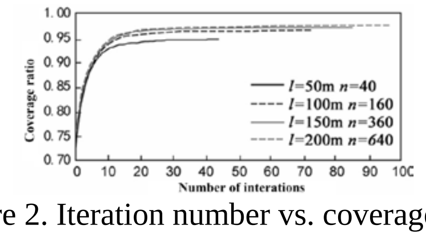
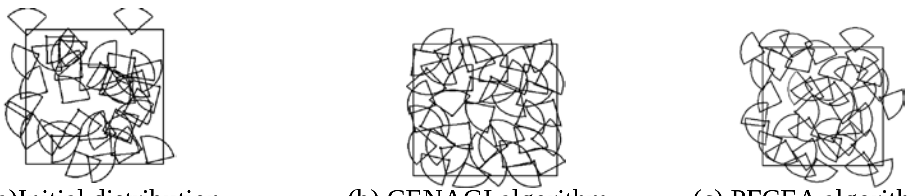


Figure 2. Iteration number vs. coverage rate

Coverage



(a)Initial distribution (b) CENAGI algorithm (c) PFCEA algorithm

Figure 3. Adjustment result drawing of CENAGI algorithm and PFCEA algorithm

Figure 3 shows the coverage condition of WSN to region R during $r = 10$ m, $\theta = \pi/2$,

$l = 50$ m and n=50 after sensor sensing direction is adjusted through CENAGI algorithm and PFCEA algorithm. In Figure 3, the coverage rates of initial distribution, CENAGI algorithm and PFCEA algorithm are respectively 64.5%, 91.3% and 71.6%. It is obvious that CENAGI algorithm improvement on coverage rate is far higher than PFCEA algorithm since region edge is not considered in PFCEA algorithm, and the sensing regions of sensors near region boundaries are still located outside the target region. Therefore, coverage rate is not greatly improved by PFCEA algorithm. The sensing region of sensors near region boundaries is adjusted by CENAGI algorithm. Therefore, most regions are located within the target region. Therefore, PFCEA algorithm coverage rate is about 1.41 times of initial distribution and 1.27 times of PFCEA algorithm.

In the paper, the following four groups of experiments are designed in order to obtain the influence of *l*, *r*, θ and *n* on coverage rate: (1) $l \in [50m, 200m]$, *r*=10m, $\theta = \pi/2$, $n = 160$; (2) $l \in 100m$, $r \in [5m, 15m]$, $\theta = \pi/2$, $n = 160$; (3) $l = 100m$, *r*=10m, $\theta \in [\pi/6, \pi]$, *n*=160; (4) $l = 100m$, *r*=10m, $\theta = \pi/2$, $n \in [50, 200]$. Figure 5(a)~(d) respectively shows the average value of results after four groups of experiments is repeated for 100 times. Figure 1 shows that sensing region size of individual directional sensor is $\theta r^2/2$. Therefore, the maximum area covered by *n* sensors in WSN is $n\theta r^2/2$. The area of rectangular monitoring region is l^2. Then, WSN coverage rate is proportional to $n\theta r^2/(2l^2)$. Four figures in Figure 5 prove the conclusion. WSN coverage rate is gradually decreased with *l* increase in Figure 5(a). WSN coverage rate is gradually increased with r increase in Figure 5(b). WSN coverage rate is gradually increased with θ increase in Figure 5(c); WSN coverage rate is gradually increased with *n* increase in Figure 5(d). Figure 5 shows that the maximum improvement value of four coverage enhancement algorithms to WSN initial coverage rate is not obtained during the maximum sensor density but during approximate sensor density because when sensor density is smaller, the mutually overlapped parts of sensor initial sensing regions are small. Therefore, the coverage rate improvement of coverage enhancement algorithm is limited under the condition. When sensor density is larger, the initial coverage rate of WSN on monitoring region has been higher. In addition, the blind zone is less under the condition. Therefore, coverage rate improvement of coverage enhancement algorithm is also limited under the condition. In addition, CENAGI algorithm has the highest coverage rate in Figure 4, which is followed by D-CENAGI algorithm. It is obvious that CENAGI algorithm can effective improve WSN coverage rate.

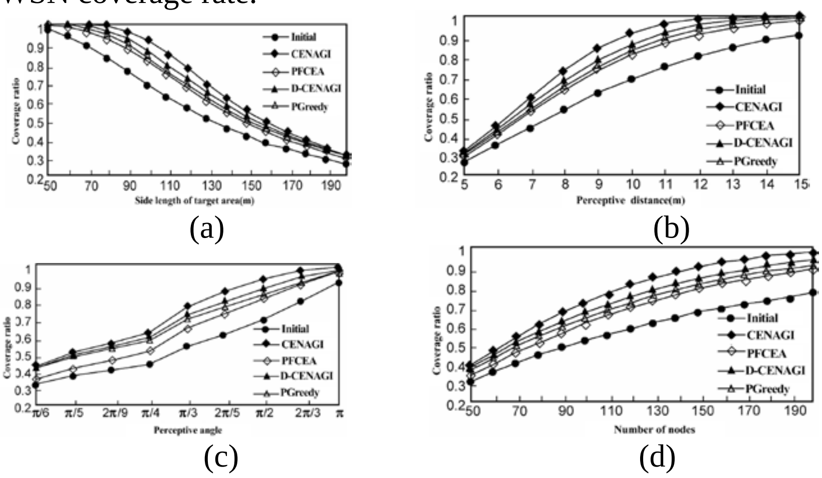
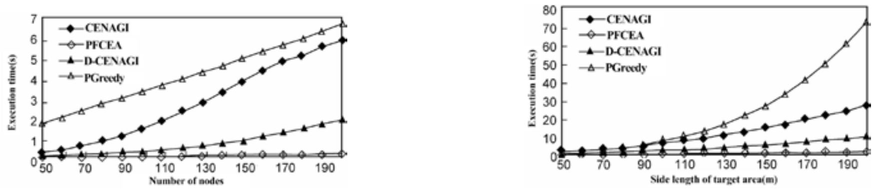


Figure 4. Coverage rates of four algorithms

Execution time. In the paper, two groups of experiments are designed in order to verify executive efficiency of CENAGI algorithm and obtain the execution time thereof: (1) $l = 100$m, *r*=10m, $\theta = \pi/2$, $n \in [50, 200]$; (2) $l = 100$m, *r*=10m, $\theta = \pi/2$, $l \in [50m, 200m]$, $\rho = 0.02\text{m}^{-2}$. The following experiment computer parameters are used: CPU Intel Pentium P6200 2.13GHz, and memory is 4GB. Figure 6(a)~(b) respectively provides the average value of results after the above two groups of experiments are repeated for 100 times.



(a) (b)

Figure 5. Execution times of four algorithms

Figure 5 shows that the execution time of four algorithms is also prolonged with the increase of sensor quantity. Since the network of sensor is calculated by sample point method in P greedy algorithm, the execution time is the longest. PECEA algorithm is simpler, and therefore the execution time is the shortest. The execution time of D-CENAGI algorithm should be shorter than CENAGI algorithm. Since sensor sensing direction rotation quantity in D-CENAGI algorithm is less than that of CENAGI algorithm, the execution time is less than that of CENAGI algorithm. Meanwhile, it is also noted that CENAGI algorithm execution can be completed within 30s under all circumstances. It is obvious that the execution time of CENAGI algorithm also can be accepted.

Conclusion

In the paper, the research situation of directional sensor network coverage enhancement algorithm is firstly analyzed. 2D coverage enhancement problem of directional sensor network is described. Then, concrete realization of CENAGI algorithm is discussed. Finally, simulation analysis is implemented on the performance of CENAGI algorithm from three aspects of convergence, coverage and execution time. Simulation results show that CENAGI algorithm has the advantages of excellent convergence, high coverage rate and suitable execution time.

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