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A Single Mobile Target Tracking in Voronoi-based Clustered Wireless Sensor Network

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Abstract—Despite the fact that the deployment of sensor networks and target tracking could both be managed by taking full advantage of Voronoi diagrams, very little few have been made in this regard. In this paper, we designed an optimized barrier coverage and an energy-efficient clustering algorithm for forming Vonoroi-based Wireless Sensor Networks(WSN) in which we proposed a mobile target tracking scheme (CTT&MAV) that takes full advantage of Voronoi-diagram boundary to improve detectability. Simulations verified that CTT&MAV outperforms random walk, random waypoint, random direction and Gauss-Markov in terms of both the average hop distance that the mobile target moved before being detected and lower sensor death rate. Moreover, we demonstrate that our results are robust as realistic sensing models and also validate our observations through extensive simulations.

Keywords—Mobile Target Tracking, Sensor Network, Clustering, Voronoi Diagram

1. INTRODUCTION

Recent advances in micro electro mechanical systems (MEMS) and wireless communication technologies are responsible for the emergence of Wireless Sensor Networks (WSNs) that deploy thousands of low-cost sensors integrating sensing, processing and communication capabilities. However, different sensor applications may pose different requirements for how good a network's coverage should be. Authors of [1] studied sensor coverage problems and categorized them into three types: *area coverage*, *point coverage*, and *barrier coverage*. The objective of the first, area coverage is to maximize the coverage for a region of interest. The objective of point coverage is similar, but it is to cover a set of points. The last, barrier coverage, aims to minimize the probability of undetected penetration through a sensor network. The choice of using a particular coverage measurement depends on the purpose of a sensor network. For instance, if the purpose is to monitor moving objects in a field, barrier coverage is most suitable. To measure barrier coverage, we consulted [2] in which the worst- and best-case coverage measurements are defined. The details of designs will be given in the next section.

Generally, sensor communication usually requires the data to be aggregated before being transmitted, which motivates the network to have efficient clustering in priority. In literature, Linked Cluster Algorithm (LCA)[3], a sensor becomes a Cluster Head(CH) if it has the highest

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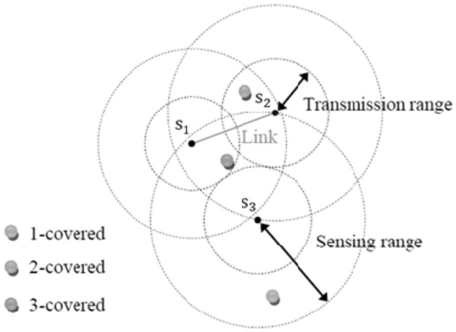


Fig. 1. Higher-order coverage

identity among all the one-hop sensors or one-hop sensors of its one-hop neighbors. The Max-Min d-Cluster Algorithm [4] generates d-hop clusters with a run-time of O(d) round, and achieves better load balancing among the CHs, generating fewer clusters than [5]. Heinzalman et al [6] proposed a distributed algorithm for micro-WSNs where sensors elected themselves CHs with some probabilities and broadcast their decisions. But this algorithm only allows one-hop clusters to be formed, which might lead to a large number of clusters. In this paper, we contributed a distributed clustering algorithm in the proposed multi-hop Voronoi diagram-based WSNs (see Section 3.). In the clustered WSN, one of the most attractive areas of sensor network was observed to be the mobile target tracking. Typical examples include establishing survivable military surveillance systems, environmental and industrial monitoring, personnel and wildlife monitoring systems requiring tracking schemes, capable of deducing kinematic characteristics such as position, velocity, and acceleration of single or multiple targets [7] of interest [8]. For the above purposes, the possible existence of targets can be inductively described as what Fig.1 shows us for simplicity.

Obviously, in Figure 1, the situation is getting more and more complicated as the density of the network increases. Our motivation is to efficiently monitor the moving multi-covered targets in Voronoi-based sensor networks by measuring the moved hop distance before being detected. We take full advantage of Voronoi diagram structure and tactfully utilize trajectory estimation technologies to predict the potential moving trajectory of the target. The main contributions of this paper are (1) an efficient sensor deployment based on higher barrier coverage; (2) An energy efficient clustering to generate Voronoi-based WSNs; (3) and a mobile target tracking scheme called CTT&MAV.

The remainder of this paper is organized as follows: the next section presents the optimized barrier coverage design; Section 3 gives the proposed clustering with energy performance analysis in detail. Section 4 illustrates the proposed intelligent mobile target tracking scheme called CTT&MAV. Section 5 conducts experiments in the Matlab simulator under a multi-covered Voronoi-based clustered sensor network. Finally, section 6 concludes the paper with future perspectives.

2. OPTIMIZED BARRIER COVERAGE DESIGN

Although maintaining full sensing coverage guarantees immediate response to the intruding targets, sometimes it is not favorable due to its high energy consumption.

2.1 New Sensor Deployment

To monitor an area, a WSN should achieve a certain level of detection performance. Due to the highly considerable cost in a given monitoring area, better *detection capacity* and *communication coverage* is critical to sequential deployment of sensors. In this paper, we explored a new approach for sensor deployment (see Fig. 2) to improve barrier coverage.

Theorem 1. Let A denote the area and *f*(A) denote barrier coverage, namely the fraction of the area that is in the sensing area of one or more sensors where sensors can provide a valid sensing measurement and Γ is the cartographic representation of an area .Then,

$$\Gamma_{f(\beta)} \gg \Gamma_{f(\alpha)} \text{ in } G = (V, E) \text{ where } E \neq \emptyset \tag{1}$$

Proof: In literature, the majority of researches prefer grid-based (see Fig. 2(a)) sequential sensor deployment. Instinctively, we get $\Gamma_{f(\beta)}$ is more efficient than $\Gamma_{f(\alpha)}$.The computational evidence is as follows:

$$\Gamma_{f(\beta)}=(2r)^2-4(\frac{\pi r^2}{4}) = (4-\pi)r^2 \approx 0.86r^2 \tag{2}$$

$$\Gamma_{f(\alpha)}= (\sqrt{3}-\frac{\pi}{2})\, r^2 \approx 0.1512r^2 \tag{3}$$

Since the calculation work is easy, we skipped the computation procedure and directly transformed to the result. The unit difference is obviously given by approximately $0.71\,r^2$. Although the difference is indistinctive when the value of r is small enough, nevertheless, for monitoring applications, accuracy is the vital consideration. The smaller the value of Γ_f, the higher possibility that a moving object will not be detected, therefore Figure 1 (b) has better detection capacity than Figure 1(a).

Theorem 2. Let H_v be a hop distance; and P_v^{up}, P_v^{same} and P_v^{lower} denotes the possible existence of CHs at the upper, same and lower layers respectively. The Triangle-based deployment is more suitable for our monitoring network in terms of higher *communication coverage*.

Proof: Figure 3 clearly shows that the Triangle-based deployment has more relay one hop

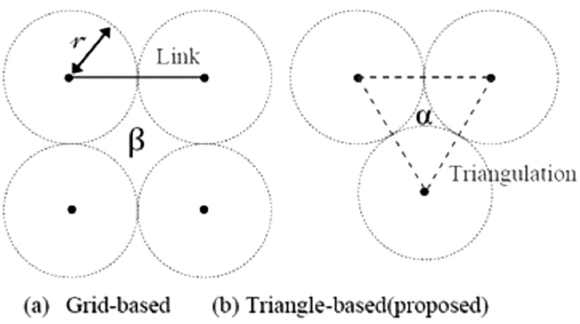
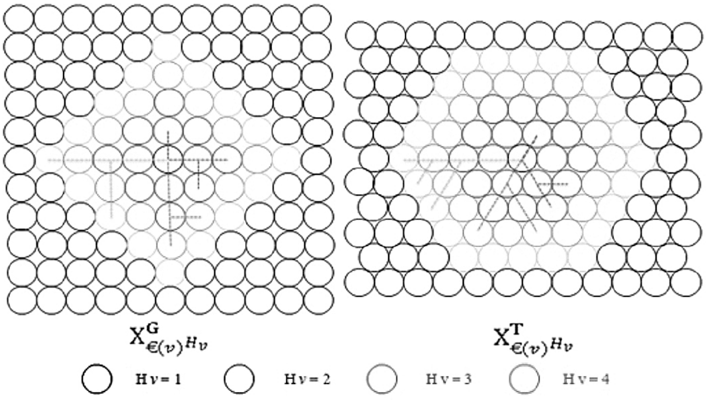


Fig. 2. Detection capacity-based sensor deployment



(a)Grid-Based (b)Triangle-based(proposed)

Fig. 3. Communication coverage-based sensor deployment

neighbors (€(v)) to relay than the Grid-based at a rate of 6:4. For multi-hops transmission, when receiving a message, a sensor (N_v) should relay it to another sensor at a cost of energy consumption. The sensor that relays should be one at the higher layer compared to N_v.

Denote H_v^{up}, H_v^{same} and H_v^{lower} represent the number of hops on the shortest routing path from N_v to a sensor at the upper, same and lower layers respectively. On the other hand, within a certain hop distance, the higher possibility of existing sensors to relay, the better. Therefore, the focus is to find out which one has more $\text{€}(V)^{Hv}$ between Figures 2 (a) and 3 (b), where $\text{€}(V)^{Hv}$: a set of H_v hop distance neighborhood sensors.

Let $X^{T}_{\text{€}(v)H_v}$ and $X^{G}_{\text{€}(v)H_v}$ denote the total number of detectable $\text{€}(V)^{Hv}$ of N_v for Triangle-based and Grid-based deployments respectively. According to Fig. 2, we easily get:

$$X^{T}_{\text{€}(v)H_v} = 3(1 + H_v)H_v \tag{4}$$

$$X^{G}_{\text{€}(v)H_v} = 2(1 + H_v)H_v \tag{5}$$

Where $H_v \geq 1$ and get $X^{T}_{\text{€}(v)H_v} \gg X^{G}_{\text{€}(v)H_v}$ that prove Triangle-based deployment is more suitable for G = (V, E) where $E \neq \varnothing$, in terms of higher communication coverage. The above gives the evidence of our optimized barrier coverage design.

3. ENERGY MODEL ENABLE CLUSTERING

In this section, we illustrate a single level energy-efficient clustering algorithm. Suppose that a single dense event occurs in a square area. The number of sensors is a Poisson random variable with E[n] = λA. Since the probability of becoming a CH is p, the CHs and non-CHs are distributed as per independent homogeneous spatial Poisson processes with intensity $\lambda_1 = p\lambda$ and $\lambda_0 = (1-p)\lambda$. To generate stochastic geometry for the proposed clustering algorithm and minimize energy cost in the network without loss of generality, we present the mathematical model of a Voronoi diagram for sensor distribution. The proposed approaches are developed with the following assumptions:

- Static Sensors (SS) are of the same capacity and functionalities. The communication is contention and error free.
- Mobile Sensors (MS) are equipped with binary sensors characterized by a sensing radius r_{s_i} for a sensor S_i. $(i \geq n)$
- The corresponding sensing range of S_i is a perfect disc denoted by $\Gamma(s_i, r_{s_i})$, and the targets will be detected by S_i if they are in its sensing range.

Clustering Parameters Setup	
n	The No. of sensors
n_c	The No. of sensors in a single cluster
D_{all}	The total length of segments, all sensors→the sink
$D_{c\to s}$	The total length of segments, all CHs→the sink
$\delta_{c\to s}$	The total energy cost, all CHs→the sink
δ	Total energy cost of data communication between sensors and the sink through a network hierarchy

Suppose a sensor located at (x_i, y_i), i=1,2,…,n. Then get

$$E[D_{all}|N = n] = 12\sum_{i=1}^{R} i^2 = 2R(R+1)(2R+1) \tag{6}$$

Where, R is the radius of the network area.

Since there are on an average npCHs with their locations independent, therefore, $D_{c\to s} = pD_{all} = 2R(R+1)(2R+1)p$. By arguments similar to [9], if N_v is a random variable denoting the number of PP0 process points in each Voronoi diagram (e.g. Figure 4) and L_v is the total length of segments connecting the PP0 process points to the nucleus in a Voronoi diagram.

$$E\,[N_v|N=n] \approx E[N_v] = \frac{\lambda_0}{\lambda_1} \tag{7}$$

$$E\,[L_v|N=n] \approx E[L_v] = \frac{\lambda_0}{2\lambda_1{}^{3/2}} \tag{8}$$

Define δ_1 to be the total energy spent by all the sensors communicating 1 unit of data to their CHs, since there are on average $(2R)^2$ CHs, namely, $p(2R)^2$ Voronoi diagrams. Let's assume that there exists a very small amount of isolated sensors so that we can ignore them without any bad influence as to the accuracy of the algorithm. Therefore, the expected value of δ_1 conditioned on N, is given by

$$E[\boldsymbol{\delta}_1|N=n] = np\,\frac{E\,[L_v|N=\alpha^2]}{r} = \frac{2(1-p)\,R^2}{r\sqrt{\lambda p}} \tag{9}$$

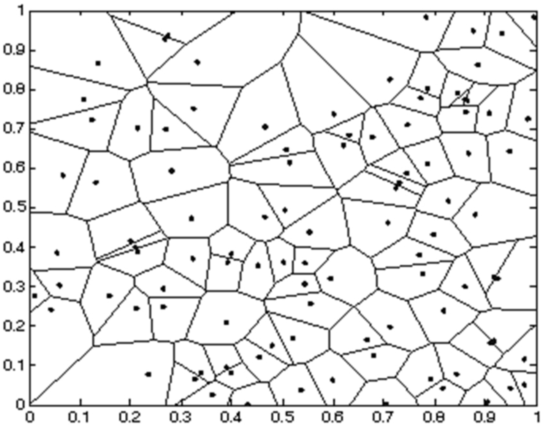


Fig. 4. Voronoi diagram based WSN for explanation

Conditioning on N, total energy spent by all the CHs communicating 1 unit of data to the sink is given by

$$E[\boldsymbol{\delta}_{c\to s}|N=n]=\frac{E[D_{c\to s}|N=\alpha^2]}{r}=\frac{2pR(R+1)(2R+1)}{r} \tag{10}$$

Then

$$E[\boldsymbol{\delta}|N=n]=E[\boldsymbol{\delta}_1|N=n]+E[\boldsymbol{\delta}_{c\to s}|N=n]=\left[\frac{2(1-p)R^2}{r\sqrt{\lambda p}}+\frac{2pR(R+1)(2R+1)}{r}\right] \tag{11}$$

E[δ] is minimized by a value of p that is a solution of the equation that gives partial derivative to (10) as follows:

$$\frac{2R(R+1)(2R+1)}{r}-\frac{R^2}{r\sqrt{\lambda p}}-\frac{R^2}{rp^{3/2}\sqrt{\lambda}}=0 \tag{12}$$

Then, get

$$-\mu p^{3/2}+p+1=0 \tag{13}$$

Where

$$\mu=\frac{2(R+1)(2R+1)}{R}\sqrt{\lambda}$$

The equation (13) has three roots, two of them are imaginary. The second derivative of the above function is positive only for the real root that is given by

Real Root:

$$\frac{1}{3\mu^2} - \frac{2^{\frac{1}{3}}(-1-6\mu^2)}{3\mu^2(2+18\mu^2+27\mu^4+3\sqrt{3}\,\mu^3\sqrt{27\mu^2+4})^{\frac{1}{3}}} + \frac{(2+18\mu^2+27\mu^4+3\sqrt{3}\,\mu^3\sqrt{27\mu^2+4})^{\frac{1}{3}}}{2^{\frac{1}{3}}(3\mu^2)} \tag{14}$$

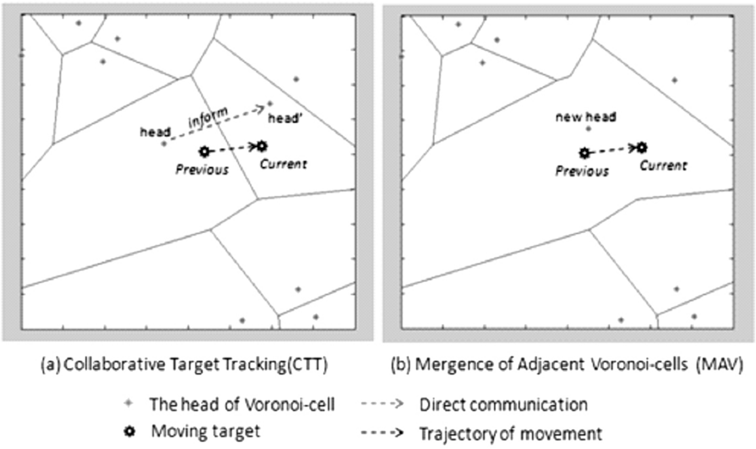
Hence, if and only if the value of p is equal to the real root, the algorithm does really minimize the energy cost.

4. INTELLIGENT MOBILE TARGET TRACKING

A CTT&MAV model was proposed for target tracking by tactfully using a Voronoi diagram. For the situations described in Figure 5, a mobile target moved from one Voronoi diagram to another during a time interval τ. As a result, the head could not detect it any more. To avoid such sudden un-detectability, the CTT&MAV was proposed to take full advantage of CTT and MAV (see Figure 5). Our choosing CTT and MAV as the better solution is based on the need to compensate for the velocity of a mobile target at the right moment moving across the Voronoi diagram boundary; this is in lieu of the fact that a Voronoi diagram combination requires considerable time which might result in failures in detecting moving mobile targets.

A. Collaborative Target Tracking (CTT):

The strong point of this strategy is that we adopt a target-closed boundary monitoring system that enables the head to quickly acquire knowledge of the boundary to which the target is currently most close. By using it, the potential target trajectory can be easily predicted by the current head. Once the target disappears suddenly from the monitoring area, the current head will immediately inform the head to be responsible for tracking the relevant target.



(a) Collaborative Target Tracking(CTT) (b) Mergence of Adjacent Voronoi-cells (MAV)

Fig. 5. Intelligent mobile target tracking (CTT&MAV)

B.Mergence of Adjacent Voronoi-diagrams (MAV):

We contiguously employ target-closed boundary monitoring to get knowledge of the potential trajectory of the mobile target. The difference with CTT is that once the mobile target goes cross the boundary line, two Voronoi diagrams divided by this boundary line will merge into one larger Voronoi diagram. Additionally, we do not perform global re-clustering; instead we just re-cluster the influenced sensors.

5. SIMULATION AND NUMERICAL RESULTS

The simulations described in this section have been performed using the Matlab environment. We made a comparison with random walk, random waypoint, random direction and Gauss-Markov mobility models [10-13]. The mobile targets enter the network one by one continuously by programming.

For monitoring sensor networks, energy conservation plays a dominant role in monitoring efficiency and accuracy. Figure 6 captured the energy levels of 100 sensors. Note: that the results represent the average performance of our proposed network over 100 simulation trials. Obvi-

Table 1. Simulation parameters

Parameter	*Value*
Network Area	$(100m)^2$
The sink	(50,50)
No. of sensors	100
Transmission range	20m
Time slots	100 (seconds)
Initial Energy/sensor	2J/battery
Message size	100 Bytes
Mobile target velocity	0~10 m/sec
E_{elec}	50 nJ/bit
E_{fs}	10 pJ/bit/m2
ε_{amp}	0.0013 pJ/bit/m4
E_{DA}	5 nJ/bit/signal

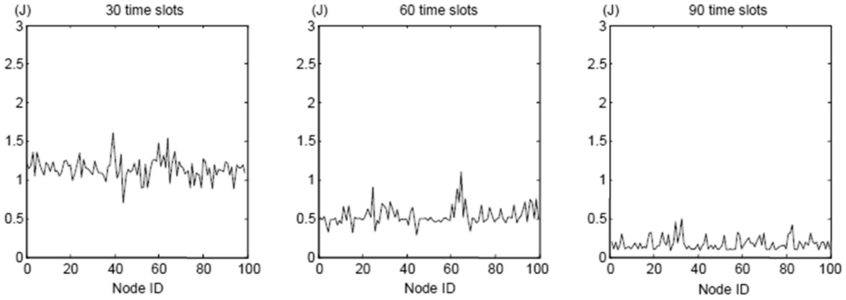


Fig. 6. Energy level of sensors at different timing

ously, it differs every time, but the differences are without significance.

Monitoring sensor death rate is essential for heterogeneous sensor networks. With the number of live nodes decreasing, the network cannot make more contributions. Thus, the network lifetime should be defined as the time when enough nodes are still alive to keep the network operational. In Figure 7, there is no doubt that our proposed CTT&MAV outperforms random walk, random waypoint, random direction and Gauss-Markov mobility models in term of lower sensor death rate. Intuitively, CTT&MAV keeps more sensors alive at any timing. For the 1st half, sensors die very slowly, while for the 2nd half, since there are few live nodes and they cannot fully take advantage of CTT&MAV, they die almost at the same speed as that of other evaluated models.

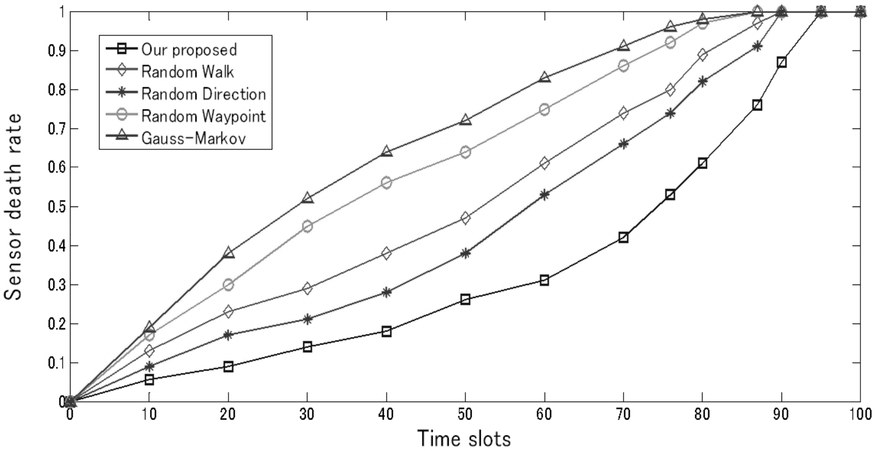


Fig. 7. Sensor death rate based on different time slots

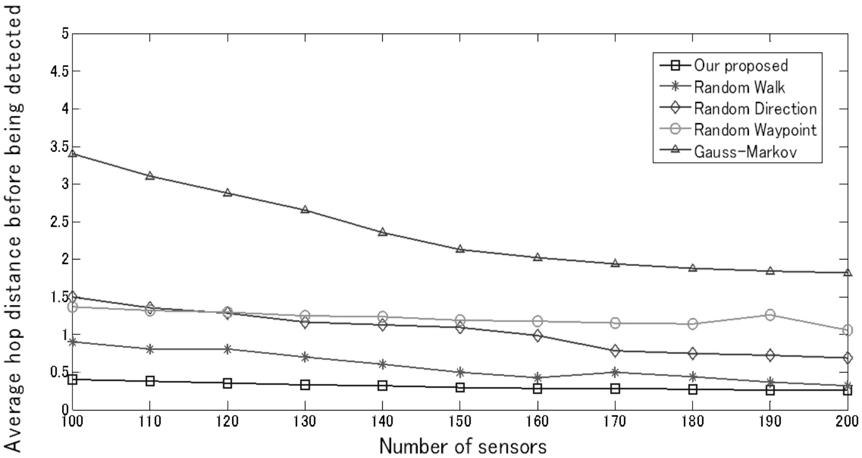


Fig. 8. Average hop distance before being detected vs. number of sensors

In this section, we present simulation results that have been conducted to assess the efficiency of the proposed CTT&MAV. The results are based on estimating the average hop distance that a mobile target can make before being detected. Figure 8 shows that our system has the best performance among the tested models. Apparently, CTT& MAV perform significantly better with the help of the proposed optimized barrier coverage and clustering algorithm.

6. CONCLUSION

In this paper, we proposed CTT&MAV to monitor moving mobile targets in a multi-covered Voronoi-based sensor network. Simulation results show that CCT&MAV performed better than *random walk*, *random waypoint*, *random direction* and *Gauss-Markov* in terms of average hop distance that a mobile target moved before being detected. Our future work will include verification of the precision of mobile target trajectory and invention of a new protocol that considers the fast mobility of each sensor as well as destroyed sensors or sudden failures in the network connectivity during communication.

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