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A k-covered Mobile Target Tracking in Voronoi-based Wireless Sensor Networks

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1. Introduction

Recent advances in micro electro mechanical systems (MEMS) and wireless communication technologies are responsible for the emergence of Wireless Sensor Network (WSN) that deploys thousands of low-cost sensors integrating sensing, processing and communication capabilities. It motivated the use of mobile sensor node in WSNs for many surveillance applications including mission-critical target tracking. One of the most attractive areas is exploited 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 (J. Janssen, et al, 2008) of interest (T.He, et al, 2006). For the above observations, the possible existence of targets can be inductively described as the Fig.1 shows for simplicity.

Despite the fact that sensor deployment sensitive target tracking could ~~both~~ be managed by taking full advantage of Voronoi diagram, less efforts were made so far. Generally, different sensor applications may pose different requirements for how good a network's coverage should be. Previous research (M.Cardei, et al, 2004) has 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 latter, 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 more suitable. To measure barrier coverage, we consulted the work (S.Meguerdichian, et al, 2005) in which the worst- and best-case coverages are defined. The detailed design will be given in the next section.

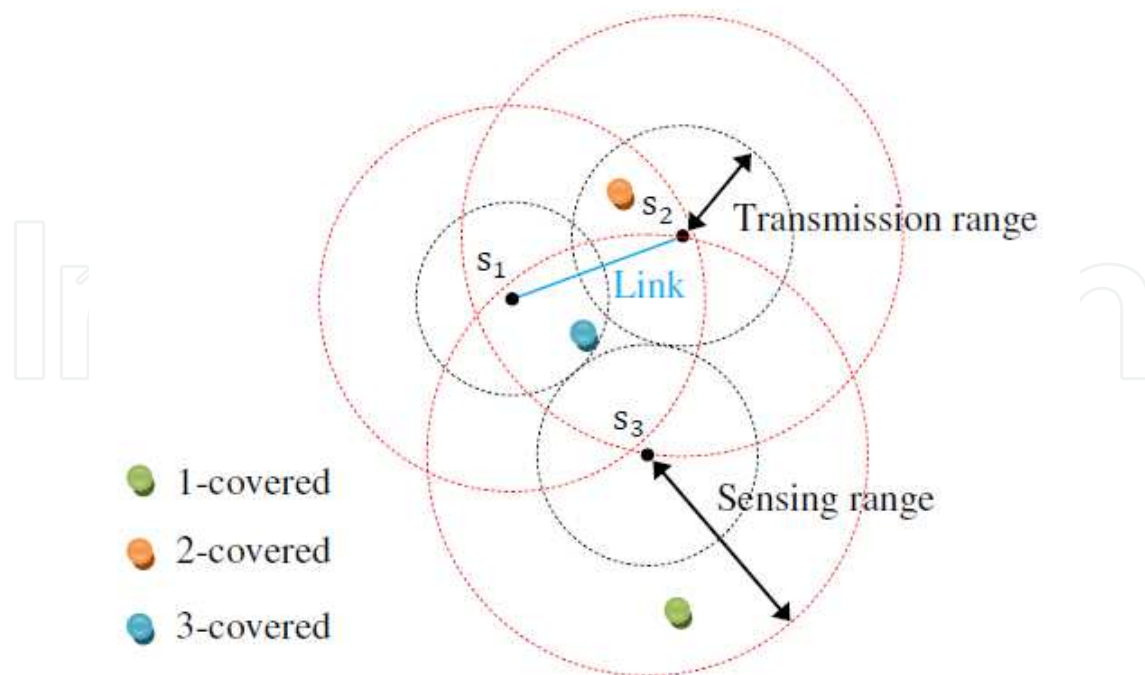


Fig. 1. Higher-order coverage

Sensor communication usually requires the data to be aggregated before being transmitted, which motivates the network to have an efficient clustering in a priority. In literature, Linked Cluster Algorithm (LCA)(D.J.Baker, et al, 1981), a sensor becomes a CH if it has the highest identity among all the one-hop sensors or one-hop sensors of its one-hop neighbors. The Max-Min d-Cluster Algorithm (A.D.Amis, et al, 2000) generates d-hop clusters with a run-time of $O(d)$ round, and achieves better load balancing among the CHs, generates fewer clusters than (A.Ephremides, et al, 1987). (W.R.Heinzelman, et al, 2000) proposed a distributed algorithm for micro-WSNs where sensors elected themselves CHs with some probabilities and broadcast their decisions. However, this algorithm only allows one-hop clusters to be formed, which might lead to a large number of clusters.

In this paper, we proposed a novel clustering algorithm to generate a multi-hop Voronoi diagram-based WSNs, one of the most attractive areas of sensor network called mobile target tracking is exploited to be performed on that base. Obviously, in Figure 1, the situation is getting more and more complicated as the density of network increases. Our motivation is to efficiently monitor the moving multi-covered mobile target in Voronoi-based sensor networks by measuring the moved hop distance before being detected. We By taking full advantage of Voronoi diagram structure, we tactfully utilized trajectory estimation technologies to predict the potential trajectory of the moving target.

Moreover, we designed a optimized barrier coverage and an energy-efficient clustering algorithm for clearing the Voronoi architecture and better energy conservation. The proposed mobile target tracking scheme (CTT&MAV) was designed to take full advantage of Voronoi-diagram boundary to improve the detectability. we enhanced PRAM algorithm (H. Meyerhenke, et al, 2005) and Final simulation results verified that our proposal outperformances random walk(T.Camp, et al, 2002), random waypoint(B.Liang, et al, 1999),

random direction(L.Lima, et al, 2007)and Gauss-Markov(C.Bettstetter, et al, 2003) in terms of reducing average hop distance that the mobile target moved before being detected and lower sensor death rate as well. Finally, we demonstrated that our results are robust to realistic sensing models and also validate the correctness through extensive simulations.

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

2. Optimized barrier coverage design

Although maintaining full sensing coverage guarantees immediate response to intrude targets, sometimes it is not favorable due to its high energy consumption. We investigate a new and more efficient approach for deploying sensors in a large scale two dimensional monitoring area.

2.1 New approach for sensor deployment

To monitor an area, 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 Figure 2) to improve barrier coverage.

Theorem 1. Let A denotes the area and $f(A)$ denotes 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 area .Then,

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

(1)

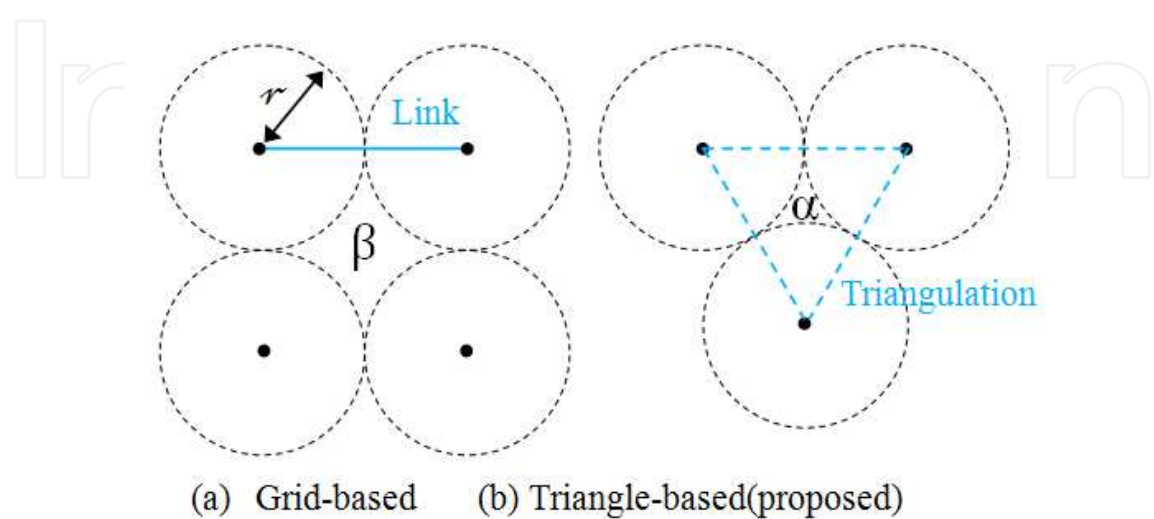


Fig. 2. Detection capacity-based sensor deployment

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

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

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

We skipped the considerably simple computation procedure and directly transformed to the result. The unit difference is obviously given by approximately $0.71r^2$. Although the difference is indistinctive when the value of r is small enough, for monitoring applications, accuracy is vital consideration. The smaller the value of Γ_f is, the higher possibility that a moving object will not be detected, therefore Figure 2 (b) has better detection capacity than Figure 2(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 layer respectively. The Triangle-based is more suitable for our monitoring network in term of higher communication coverage.

Proof: Figure 3 clearly shows that Triangle-based has more relay one hop neighbors ($\epsilon(v)$) to relay than 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 price of energy consumption. The sensor to relay should be one at the higher layer compared to N_v .

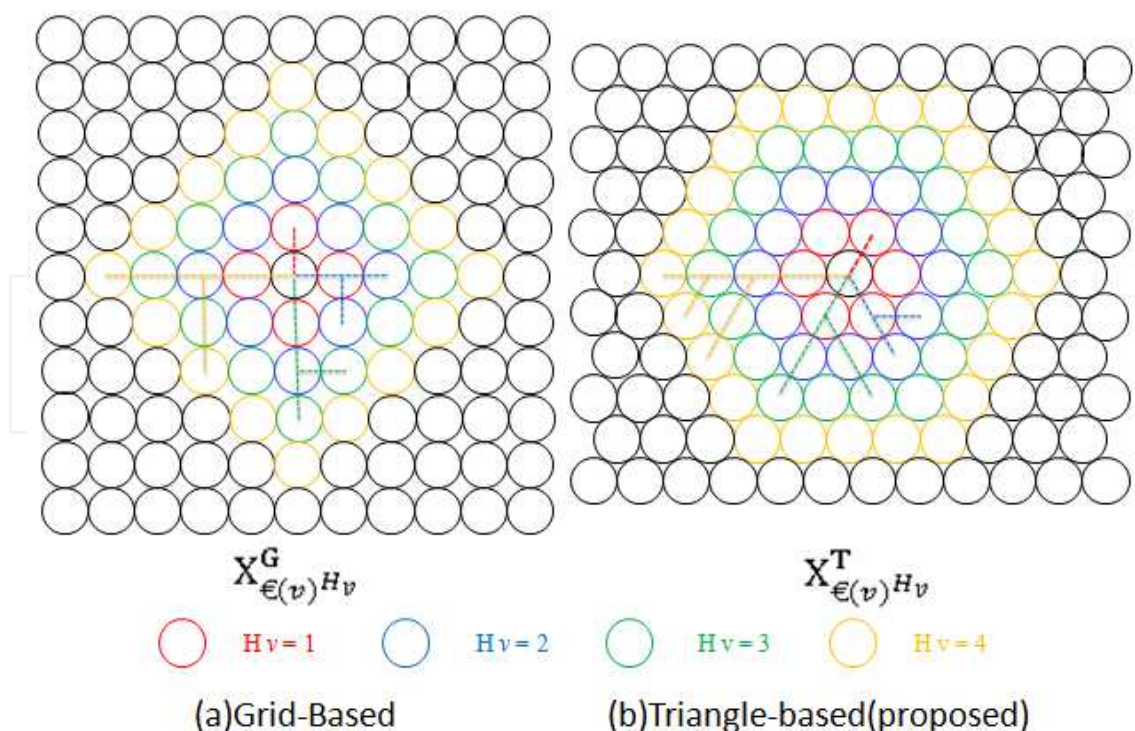


Fig. 3. Communication coverage-based sensor deployment.

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 layer 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 $\epsilon(v)^{H_v}$ between Figure 3 (a) and Figure 3 (b), where $\epsilon(v)^{H_v}$: a set of H_v hop distance neighborhood sensors.

Let $X_{\epsilon(v)^{H_v}}^T$ and $X_{\epsilon(v)^{H_v}}^G$ denote the total number of detectable $\epsilon(v)^{H_v}$ of N_v for Triangle-based and Grid-based respectively. According to Fig. 3, we easily get:

$$X_{\epsilon(v)^{H_v}}^T = 3(1 + H_v)H_v \quad (4)$$

$$X_{\epsilon(v)^{H_v}}^G = 2(1 + H_v)H_v \quad (5)$$

Where $H_v \geq 1$ and get $X_{\epsilon(v)^{H_v}}^T \gg X_{\epsilon(v)^{H_v}}^G$ that prove Triangle-based is more suitable for $G = (V, E)$ where $E \neq \emptyset$, in terms of higher *communication coverage*.

The above observations show evidences for proving the efficiency of the proposed optimized barrier coverage design.

3. Mathematical modeling of Voronoi-based WSN based on energy consumption

In this section, we present the mathematical modeling of Voronoi diagram for sensor node distribution. The proposed approaches are developed with the following assumptions:

- Static Sensor Nodes are of the same capacity and functionalities. The communication is contention and error free.
- Mobile Sensor Nodes are equipped with binary sensors characterized by a sensing radius R_{s_i} for a sensor node s_i . ($i \leq n$)
- The corresponding sensing range of s_i is a perfect disc denoted by $\Gamma(s_i, R_{s_i})$, and the mobile targets will be detected by s_i if they are in its sensing range (see Figure 1).

A multi-hop WSN was modeled by an undirected graph $G = (V, E)$ where V , $|V| = n$, is the set of wireless sensor nodes and there exists an edge $\{s_u, s_v\} \in E$, if and only if s_u and s_v can mutually receive each other's transmission. Namely, two sensor nodes are considered neighbors if the Euclidean distance is smaller or equal to the transmission range r . The set of k -hop neighbors of s_v is denoted by $\epsilon(s_v)^k$.

Let \mathcal{M} be a metric space, and $\mathcal{M} \times \mathcal{M} \rightarrow \zeta$ denoting the Euclidean distance on \mathcal{M} . A set of sensor nodes having their coordinates in \mathcal{M} is denoted by $\chi = \{\phi_i, 1 \leq i \leq n\} \subseteq \mathcal{M}$. The Voronoi diagram associated to χ is the unique subset called Voronoi diagram related to $\{\phi_i, 1 \leq i \leq n\}$. In literature, many algorithms have been proposed to determine the Voronoi diagram in a 2D space. In this section, we define the k -Voronoi diagram construction model based on the cooperation of χ elements. Our strategy is based on the PRAM algorithm (H. Meyerhenke, et al, 2005). The major merit is that the algorithm is performed in a recursive

manner where the $(k-1)$ -Voronoi diagram is used to collaboratively compute the k -Voronoi diagram. Let's define the subsets of χ includes the nearest elements to be ψ_i^k which can help finding the elements closer to the most distant neighbouring.

1. **Input:** a set of χ of sensor nodes and Voronoi of order $(k-1)$

2. Divide each region by $\psi_i^k \subset \chi$ into subregions

3. Merge equivalent new sub-regions who are tightly relevant to the neighboring ψ_i^{k-1}

4. Update the current edges and vertices.

5. **Output:** k -Voronoi diagram

To generate a single level energy-efficient clustering algorithm, suppose that a single event is densely happened in a square area. The number of sensors is a Poisson random variable with $E[n] = \lambda A$. 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 Voronoi diagram for sensor distribution.

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

Table 1. Simulation parameters Setup

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

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

(6)

Where, R is the radius of the network area.

Since there are on an average np CHs with their locations independent, therefore, $D_{c \rightarrow s} = pD_{all} = 2R(R + 1)(2R + 1)p$. By arguments similar to (S.G.Foss, et al, 1996), 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 that connect the PP0 process points to the nucleus in a Voronoi diagram.

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

(7)

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

(8)

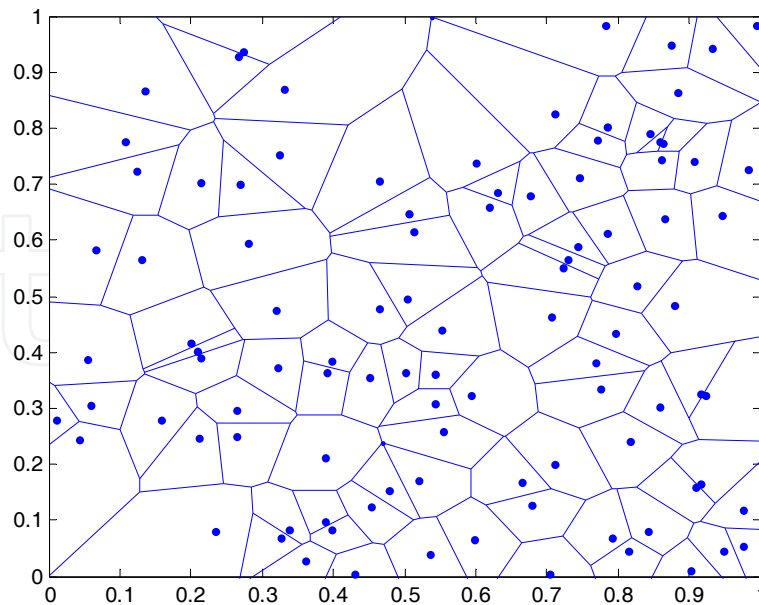


Fig. 4. Voronoi diagram based WSN

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 assume that there exists very small amount of isolated sensors so that ignore them without any bad influence to the accuracy of the algorithm. Therefore, the expected value of δ_1 conditioning on N , is given by

$$E[\delta_1|N=n]=np \frac{E[L_v|N=\alpha^2]}{r} = \frac{2(1-p)R^2}{r\sqrt{\lambda p}} \quad (9)$$

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

$$E[\delta_{c \rightarrow s}|N=n] = \frac{E[D_{c \rightarrow s}|N=\alpha^2]}{r} = \frac{2pR(R+1)(2R+1)}{r} \quad (10)$$

Then

$$E[\delta|N=n] = E[\delta_1|N=n] + E[\delta_{c \rightarrow s}|N=n] = \left[\frac{2(1-p)R^2}{r\sqrt{\lambda p}} + \frac{2pR(R+1)(2R+1)}{r} \right] \quad (11)$$

$E[\delta]$ is minimized by a value of p that is a solution of equation that gives partial derivative to (10) as follow:

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

Then, get

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

Where

$$\mu = \frac{2(R+1)(2R+1)}{R} \sqrt{\lambda} \quad (14)$$

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:

$$\frac{1}{3\mu^2} - \frac{\frac{1}{2^{\frac{1}{3}}}(-1-6\mu^2)}{3\mu^2(2+18\mu^2+27\mu^4+3\sqrt{3}\mu^3\sqrt{27\mu^2+4})^{\frac{1}{3}}} + \frac{(2+18\mu^2+27\mu^4+3\sqrt{3}\mu^3\sqrt{27\mu^2+4})^{\frac{1}{3}}}{2^{\frac{1}{3}}(3\mu^2)} \quad (15)$$

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

3.1 Simulations on energy efficiency of clustering for generating Voronoi-based WSN

In this section, we simulated the proposed algorithm with totally n distributed sensors in a square of 1000 sq. units. Energy dissipation follows Low Energy Adaptive Clustering Hierarchy (LEACH) protocol. The experiments were conducted with the communication range r was assigned to be 1 unit and total number of sensors n is assigned to be 400, 1600, 2500 with $R=10, 20, 25$ respectively. Moreover, the processing center is assumed to be at the center of the network area. Don't consider the unexpected errors and influences from outside circumstance.

For the simulation experiments, considered a range of possible value of the probability (p) less than 0.1 for most of potentials. For each of possible value of p , compute the density of Poisson process λ for generating the network under different network conditions. The results are provided in Figure 5. In figure 5, the proposed algorithm was used to detect the boundary of the network with $R=10, R=20$ and $R=25$ respectively. Then vary the value of the density of Poisson process (λ) to get the willing values of p for computation on minimized energy cost (δ). However, it shows that the value of p decreases as the value of λ increases stably at an interval $\{0.03, 0.1\}$. To achieve p with a value of smaller than 0.03, we have to manage the rapidity of changing λ at a high value since clustering algorithm are well working in a densely deployed large scale WSNs, while to achieve p in excess of 0.1, we don't need to concern too much because there are few sensors randomly distributed in such a large scale area with λ pretty small that indicates sensors are difficult to get communicate with each other, they are of great potential to be geographically separated. In this case, the algorithm produce huge amount of *isolated sensors* that is object to the assumption and beyond our consideration.

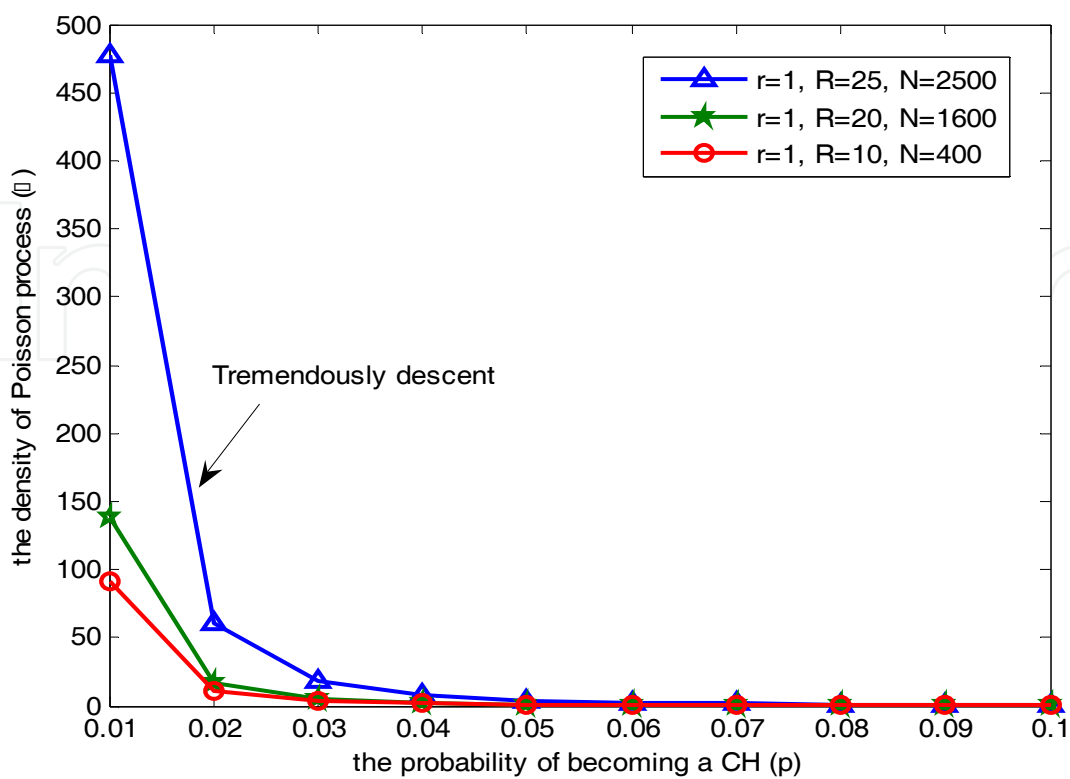


Fig. 5. The computation of parameters $\{p, \lambda\}$

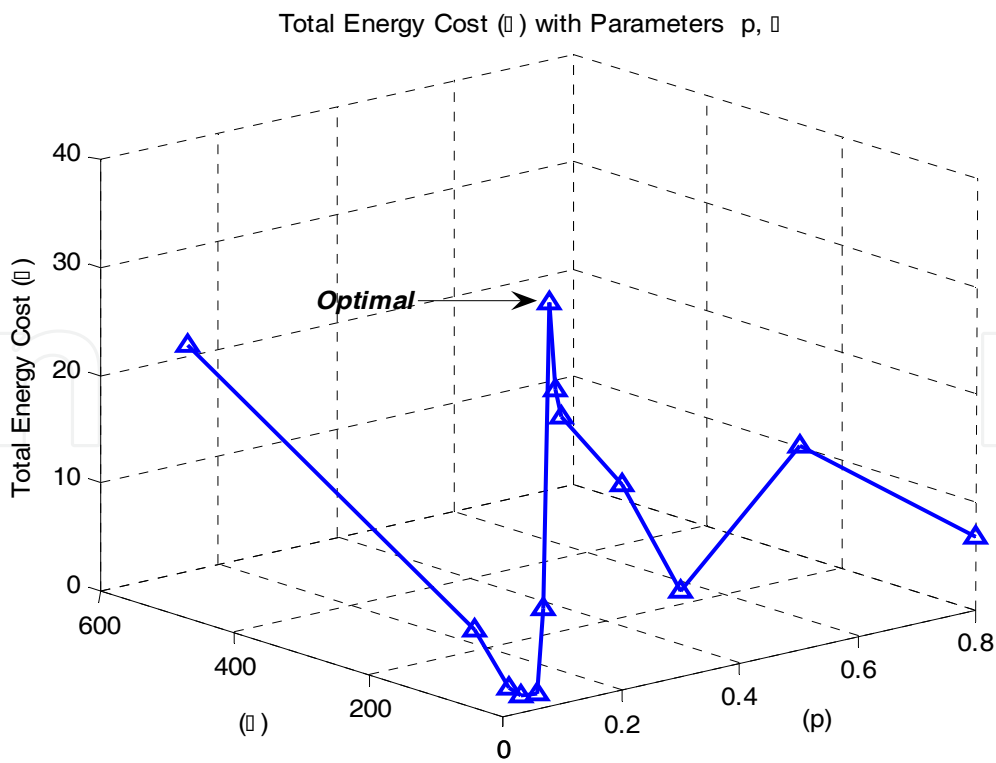


Fig. 6. Optimal value p for minimizing total energy cost (δ)

Each data point in Figure 6 corresponds to the average energy cost over 100 experiments. It is verified that the energy spent in the network is indeed minimized at the theoretically optimal value of p at “0.08” under a network condition of $\{r=1, R=10, N=400\}$ in a randomly distributed large scale Voronoi cell based WSNs. The optimal value of p here will be of more considerable for the future research. Now, let’s do comparative study between popular Max-Min D-Cluster algorithm and the proposed clustering algorithm in terms of minimizing energy cost.

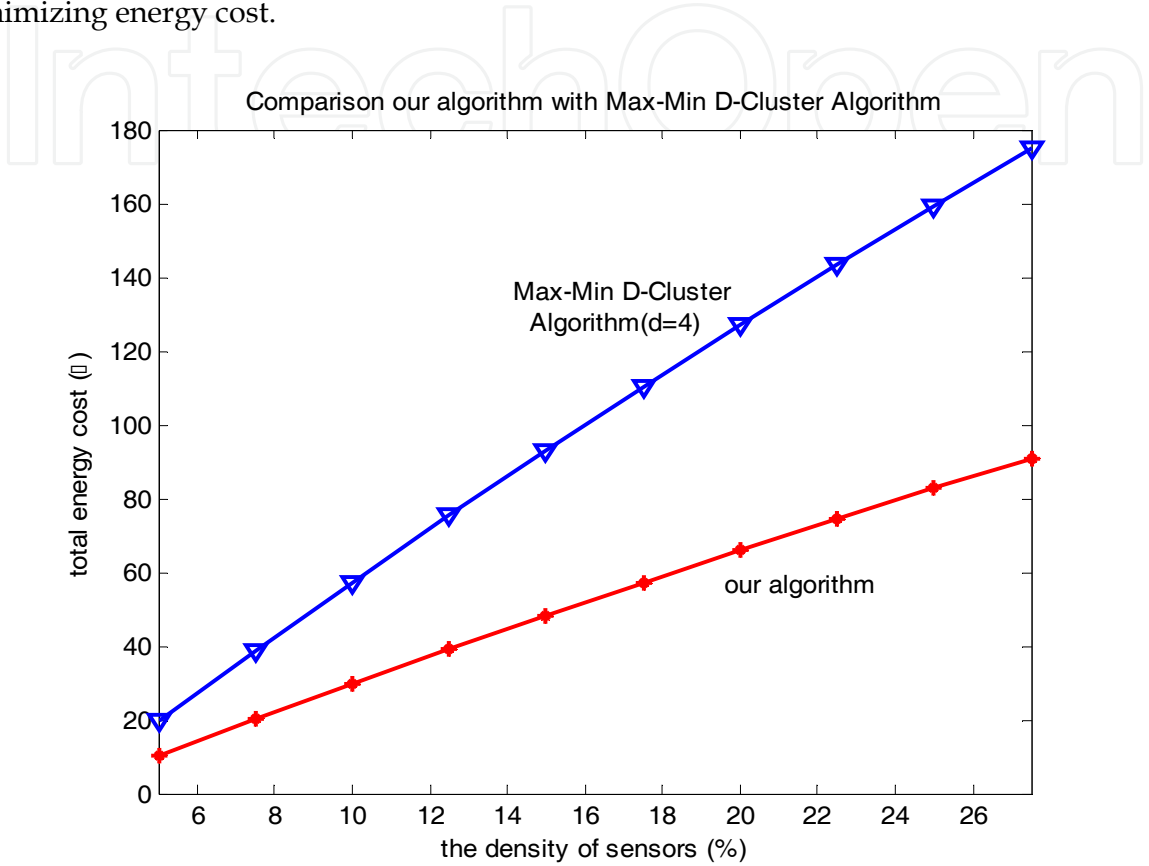


Fig. 7. Comparison with Max-Min D-Cluster algorithm

In Figure 7, the pre-obtained optimal values of all the critical parameters of the proposed algorithm in simulation model are used to evaluate the performance of the algorithm. At same time, we evaluated the Max-Min D-Cluster Algorithm with $d=4$. The result (e.g. Figure 7) clearly verifies that the algorithm performances better in terms of energy cost in the network under this network specification.

4. Mobility model for k-covered mobile target tracking

In this section, we proposed a mobility model for k-covered target tracking applications based on Voronoi diagram. The following gives a condition for a Voronoi diagram partly uncovered. Let \mathcal{P} be a set of sensor node physical positions. If there exists s_u , such that $d(s_v, s_u) > 2R_{s_v}$, then s_u is not fully covered in $\Gamma(s_v, R_{s_v})$.

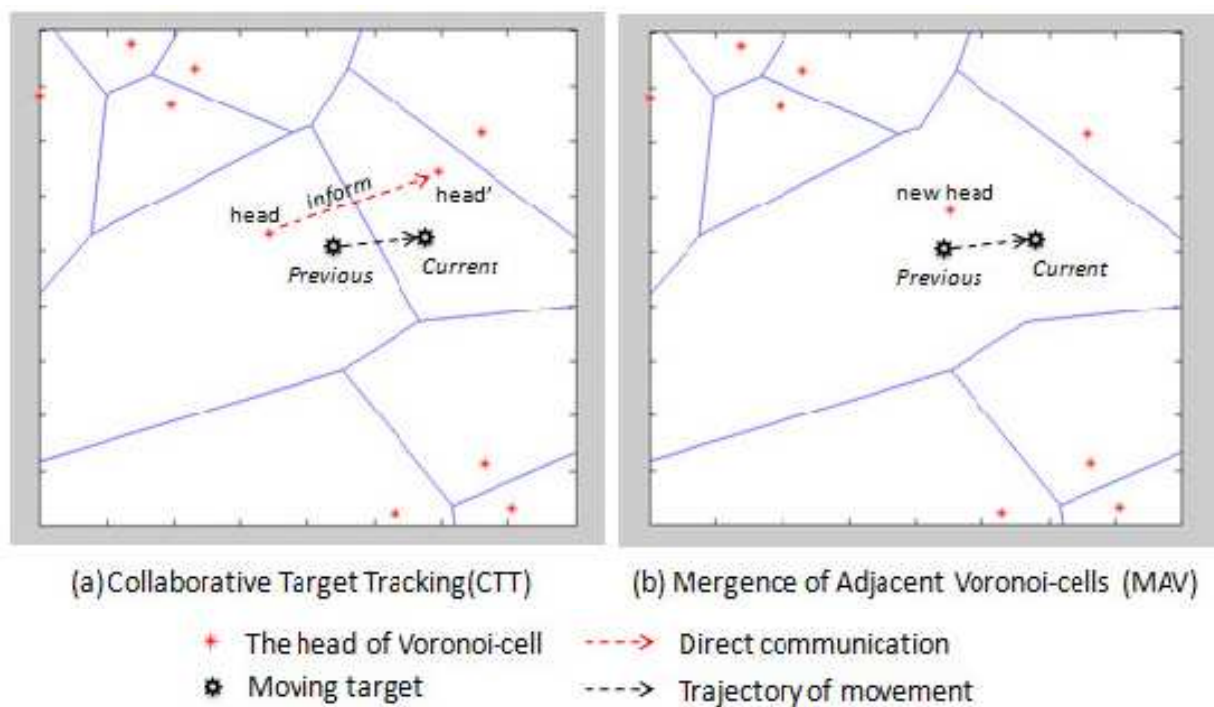


Fig. 8. Mobile target tracking strategy in Voronoi-based WSN

For the situations described in Figure 8, a mobile target moved from one Voronoi diagram to another during a time interval τ . As a result, head cannot detect it any more. To avoid such a sudden undetectability, two intelligent tracking strategies were proposed as follows:

- 1) **Collaborative Target Tracking (CTT):**
The network topology keeps the same. The major merit is that we adopt a target-closed boundary monitoring that enables the *head* to have a quick knowledge of the boundary line to which the target is current most closed. By using it, the potential mobile target trajectory can be easily predicted by current *head*. Once the mobile target disappeared suddenly from the monitoring area, the current head will immediately inform the *head'* to be responsible for tracking the entered target. (see Figure 8(a)).
- 2) **Mergence of Adjacent Voronoi-diagrams (MAV):**
We keep using mobile target-closed boundary monitoring to get knowledge of the potential trajectory of the mobile target. The difference from CTT is that once the mobile target went cross the boundary line, two Voronoi diagrams divided by this boundary line will merge into one larger Voronoi diagram (see Figure 8(b)). Additionally, we do not need to perform the global re-clustering, instead just re-clustering the ~~influenced~~ involved sensor nodes in this case.

5. Simulations of k-covered mobile target tracking in Voronoi-based wireless sensor network

The simulations described in this section have been performed using the Matlab environment. We made a comparison with random walk (T.Camp, et al, 2002), random

waypoint (B.Liang, et al, 1999), random direction(L.Lima, et al, 2007)and Gauss-Markov (C.Bettstetter, et al, 2003). The mobile target enters the network one by one continuously by programming.

Parameter	Value
Network Area	$(100\text{m})^2$
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/m ²
ϵ_{amp}	0.0013 pJ/bit/m ⁴
E_{DA}	5 nJ/bit/signal

Table 2. Simulation parameters

For monitoring sensor network, energy conservation plays a dominated role in monitoring efficiency and accuracy. Figure 9 captured the energy levels of 100 sensors. *Note:* that the results represent the average performance of our proposed network over 100 times simulation trials. Obviously, it differs every time, but makes no distinction.

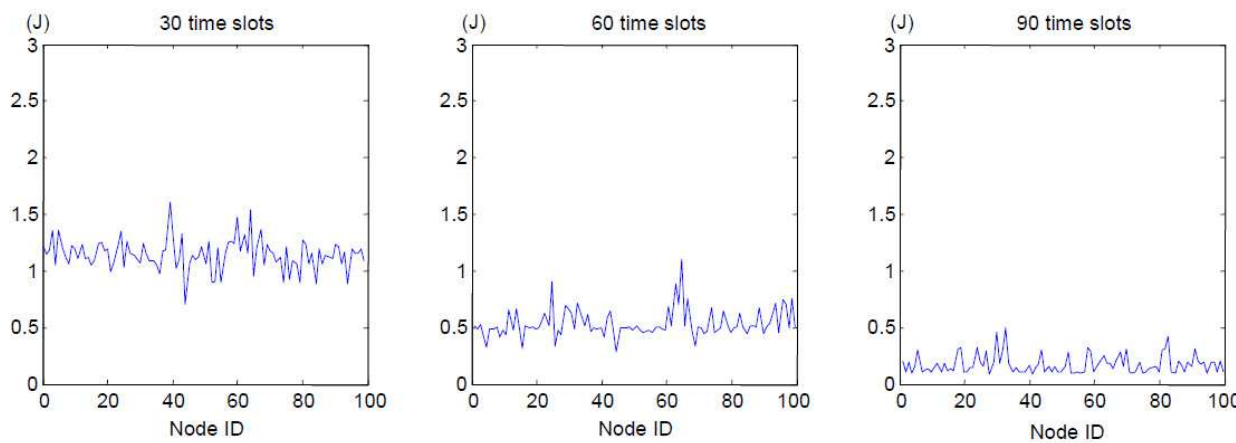


Fig. 9. Energy level of sensors at different timing

Sensor death rate is essential for heterogeneous sensor network. With the number of alive 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 10, it is no doubt that our proposed CTT&MAV outperformance *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 few alive nodes cannot fully take advantage of CTT&MAV, they die almost at the same speed as that of other evaluated models.

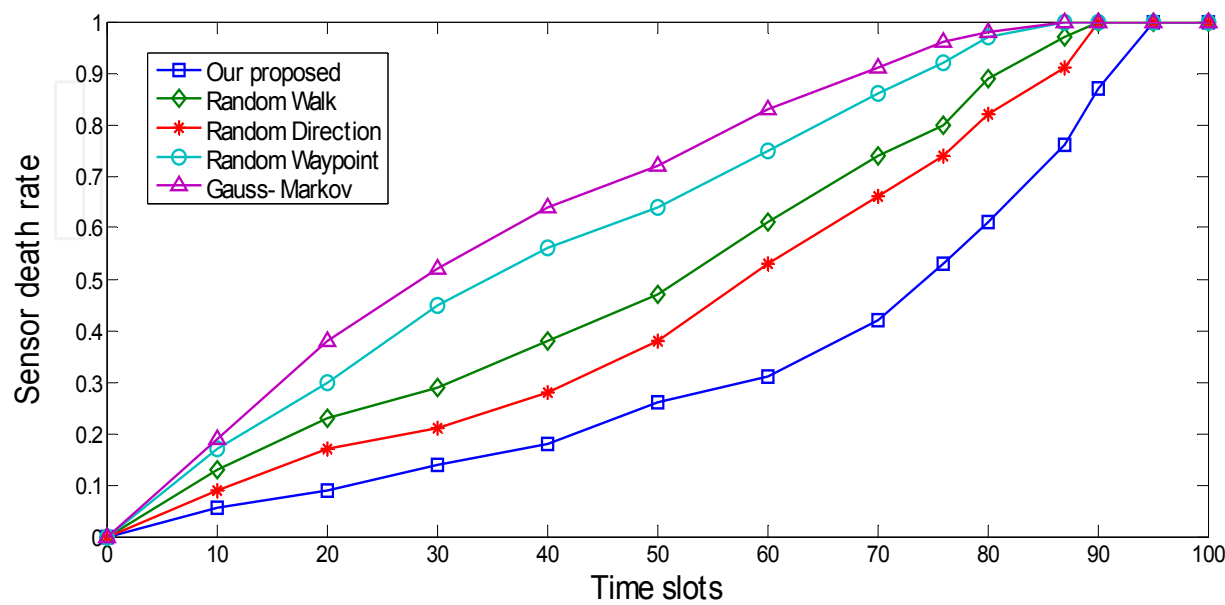


Fig. 10. Sensor death rate based on different time slots (k=2)

In this subsection we present the results of the simulations that have been conducted to assess the efficiency of the proposed CTT&MAV. It is based on estimating the average hop distance that mobile target can make before being detected. Figures 11 show that our proposed has the better performance among the tested models. Apparently, CTT& MAV perform significantly better with the help of Section 2 and Section 3.

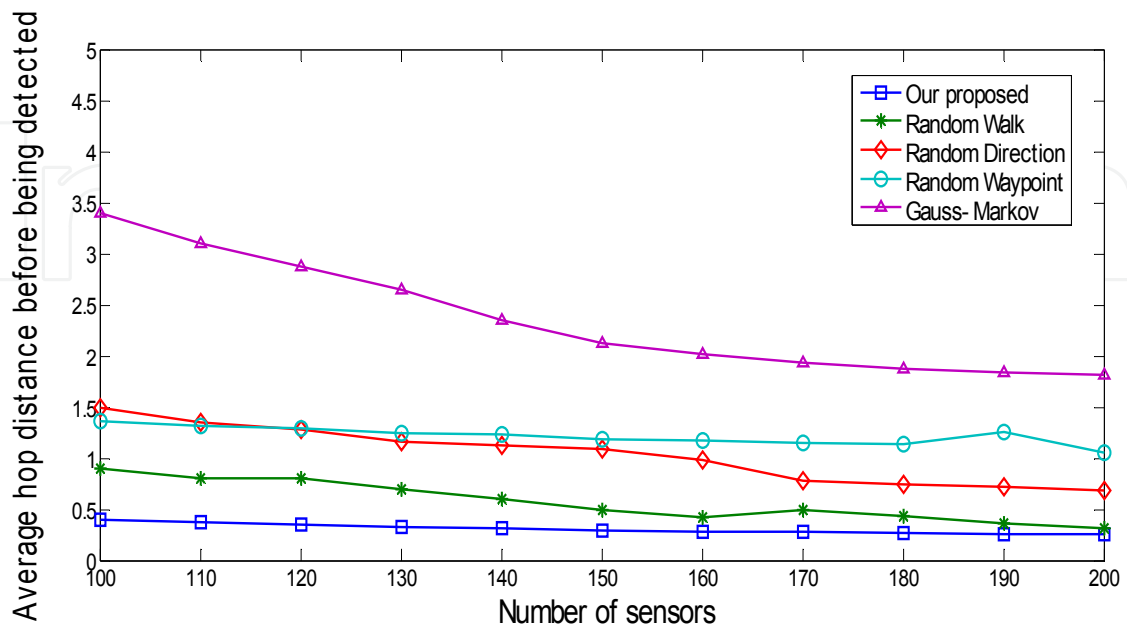


Fig. 11. Average hop distance before being detected (k=2)

6. Conclusion

In this chapter, we proposed two intelligent tracking strategies to monitor the moving multi-mobile target in a k -covered Voronoi-based WSNs. The current simulations based on the simplified 2-covered network region with one mobile target show that CCT and MAV performed better than *random direction* in term of average distance that the target moved before being detected. However it is currently insufficient, we will simulate more based on the uncertain k and the number of mobile targets to prove our hypothesis. In a word, mobile target tracking using Voronoi diagram is a meaty theme. Our future work will include verification of precision of mobile target trajectory and invention of a new protocol that consider the fast mobility of each sensor as well as destructive sensors or sudden failures in the network connectivity during communication.

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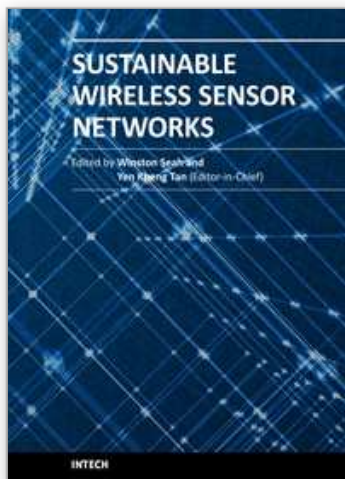
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Wireless Sensor Networks came into prominence around the start of this millennium motivated by the omnipresent scenario of small-sized sensors with limited power deployed in large numbers over an area to monitor different phenomenon. The sole motivation of a large portion of research efforts has been to maximize the lifetime of the network, where network lifetime is typically measured from the instant of deployment to the point when one of the nodes has expended its limited power source and becomes in-operational “ commonly referred as first node failure. Over the years, research has increasingly adopted ideas from wireless communications as well as embedded systems development in order to move this technology closer to realistic deployment scenarios. In such a rich research area as wireless sensor networks, it is difficult if not impossible to provide a comprehensive coverage of all relevant aspects. In this book, we hope to give the reader with a snapshot of some aspects of wireless sensor networks research that provides both a high level overview as well as detailed discussion on specific areas.

How to reference

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