Critical Sensing Range for Camera Sensor Networks

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Abstract

In camera sensor networks (CSNs), full view coverage, in which any direction of any point in the operational region is covered by at least one camera sensor, is of great significance since image shot at the frontal viewpoint considerably increases the possibility to recognize the object. However, finding the critical condition to achieve full view coverage in CSNs remains an open question. In this paper, we analyze both the static and mobile random deployed camera sensor networks. A centralized parameter – equivalent sensing radius (ESR) – is defined to evaluate the critical requirement for asymptotic full view coverage in heterogeneous CSNs. We derive ESR for full view coverage under static model, 2-dimensional random walk mobility model, 1-dimensional random walk mobility model and random rotating model. We also proof that the critical ESR to achieve almost surely coverage is 1.225 times of the critical ESR to achieve coverage with high probability, and extend the result to homogeneous network. We then discuss the impact of various mobility patterns on sensing energy consumption and study the power-delay tradeoff and show that random walk mobility model can decrease the sensing energy consumption under certain delay tolerance. To our knowledge, our work is the very first that derive the critical condition to achieve full view coverage in mobile heterogeneous CSNs.

1 Introduction

Coverage, a critical performance metric in Wireless Sensor Networks (WSNs), is used to measure how well a field is monitored by sensors within the field. It is significant in many applications, such as security surveillance, intrusion detection in battlefield or military zone and so forth. Recently, Camera Sensor Networks (CSNs) have attracted an increasing amount of attention, since the image or video provided by camera sensors can considerably enrich the information of the monitored region. Such networks have prospective applications including traffic avoidance, environmental monitoring, and industrial process control [1]. However, the camera sensors do not possess omnidirectional sensing ability as traditional ones. On the contrary, they can only sense within an angle of view, beyond which it is unable to capture any information, which leads to new problems and requirements for networks.

There are many investigations for networks of traditional sensors. In [2], Kumar studied the asymptotic k-coverage in a mostly sleepy stationary sensor network, and in [3], Srikant *et al.* considered the failure probability and obtained the necessary and sufficient condition to achieve asymptotic full coverage. In [4], [5], [6] and [7], the authors mainly focused on the barrier coverage problems with traditional sensors separately. Besides, in [8] and [9], the authors studied deployment scheme to achieve multiple coverage and connectivity. And in [10], Bai and Kumar proposed a deployment pattern to achieve both coverage and connectivity.

However, compared to the relative mature study on the coverage in traditional sensor networks, studies on the coverage of CSNs are quite limited. In [11], Wang and Cao first proposed a novel concept in the judgement of coverage in CSNs, called full view coverage. An object is full view covered if its viewed direction is always closely enough to its facing direction, wherever it actually faces. Since the frontal image could provide a higher probability for computer recognition systems to successfully recognize an object [12], it is of great significance to develop a CSN being able to achieve full view coverage.

To construct such networks, it is essential to understand the required conditions for full view coverage, e.g. sensing radius, angle of view, or deployment density. In [11], Wang and Cao provided a sufficient condition under random and uniform deployment, and a critical (i.e. both necessary and sufficient) condition under triangle lattice based deployment. And in [13], the authors analyzed the necessary and sufficient condition to achieve full view coverage separately. Other existing works on CSNs are mainly concerned with full view barrier coverage as in [14] and [15], which suggests the critical condition to achieve full view area coverage in mobile camera sensor network still remains an open problem.

In this paper, we concentrate on the critical condition of full view coverage under uniform deployment. We consider asymptotic coverage for mathematical convenience as in [16], which means that the total number of cameras approaches to infinity. The coverage problem of a unit square is converted into the coverage of a dense grid in it, which is a common method in the analysis of area coverage [2]. Following this route, we derive the critical condition of full view coverage under uniform deployment.

We also investigate the impact of mobility. In [17], Liu proposed that mobility could improve coverage performance, since it could reduce the detection time of intruders. Saipulla and Liu in [18] considered the limited mobility for barrier coverage which distinguish their work. Besides, mobility was found to increase the capacity [19], improve connectivity [20], [21] and help security [22] in ad-hoc networks. All of these works reveal the significance of analysis of mobility. In this paper, we study the critical sensing range for full view coverage under three different mobile patterns and compare them with the static model to verify their advantages.

Moreover, we take heterogeneity of camera sensors into consideration. It is intuitive to treat CSNs as a heterogeneous network, since camera sensors may come from different manufacturers and thus have different sensing parameters, or the sensing capability of cameras will decline as time passes by or under different obstruction of terrains. To deal with heterogeneous cameras, we divide them into different groups according to their sensing parameters as the cases in [23] and [24]. The *equivalent sensing radius* (ESR) are defined later to help analyzing in static and mobile condition separately. This index summarizes different sensing parameters of all the cameras, and therefore represents the overall requirements for cameras in CSNs.

Our main contributions are highlighted as follows.

- We provide the critical condition of full view coverage under four different static or mobile patterns, which could help the engineers to design the CSN according to certain engineering requirements by balancing coverage performance and sensing energy consumption.

- We define the ESR for static and mobile camera sensor network, which could provide intrinsic understanding of heterogeneous camera sensor network. For static model, $r = \sqrt{\sum_{y=1}^{u} c_y \frac{\phi_y}{2\pi} r_y^2}$. For 2-dimensional random walk mobility model and 1-dimensional random walk mobility model, $r = \sum_{y=1}^{u} c_y \frac{\phi_y}{2\pi} r_y$. And for random rotating mobility model, $r = \sqrt{\sum_{y=1}^{u} c_y (2-(1-\frac{\phi_y}{2\pi})^2) r_y^2}$.

- Compared with static model, 2-dimensional random walk mobility and 1-dimensional random walk mobility reduces the sensing energy consumption by the order $\Theta(\frac{\log n + \log(\log n)}{n\theta})$ [*], at the expense of $\Theta(1)$ delay under uniform deployment.

The remainder of the paper is organized as follows. Basic models and definitions are described in Section 2. We present the main result for heterogeneous network in Section 3, and We show the geometric analysis and preliminaries in Section 4. In Section 5, we study the static model and derive the ESR to achieve full view coverage. We study 2-dimensional random walk mobility model, 1-dimensional random walk mobility model and random rotating model and derive the corresponding ESR in Section 6. We extend our result to homogeneous network in Section 7. In Section 8, we study the power-delay tradeoff. In Section 9, we conclude the paper and discuss about the future work.

2 Notations and Model

In this section we present the sensing and deployment model of the camera sensors used in our paper, introduce our mobility patterns, and describe several performance measures, like the definition and meaning of full view coverage and equivalent sensing range, to assess the coverage performance of static and mobile heterogeneous CSNs.

[*]The following asymptotic notations are used throughout this paper. Given non-negative functions $f(n)$ and $g(n)$:

(a) $f(n) = \Theta(g(n))$ means that for two constants $0 < c_1 < c_2$, $c_1 g(n) \leq f(n) \leq c_2 g(n)$ for sufficiently large n.

(b) $f(n) \sim g(n)$ means that $\lim_{n\to+\infty} \frac{f(n)}{g(n)} = 1$.

(c) $f(n) = o(g(n))$ means that $\lim_{n\to+\infty} \frac{f(n)}{g(n)} = 0$.

2.1 Deployment Scheme and Sensing Model

In this paper, we assume the operational region of the sensor network is a unit torus square, such that we don't need to consider strategy when sensors reach the edge of the area, and focus on the general cases. Actually coverage problem near the boundaries differs significantly from general situations, but it is currently beyond the scope of this paper.

We assume in the operational region n sensors are randomly and uniformly deployed, independent of each other, which is widely recognized as proper estimations for randomly distributed sensors. The random strategy is favored in the situation that the operational region is inimical and hostile, or that it is expensive and difficult to place sensors by human or programmed robots. Under such circumstance, wireless sensors might be sprinkled from aircrafts, delivered by artillery shell, rocket, missile or thrown from a ship, instead of being placed by human or programmed robots.

A camera sensor S can sense perfectly in a sector of radius r and angle ϕ, but will not sense outside the sector. Without confusion, S also denotes the location of the sensor. The angular bisector of ϕ is recognized as *orientation* of S, denoted by $\vec{f}$. This model is commonly used in literature [25] and [26], called *binary sector model*. Further, since the quality of information provided by a camera is sensitive to its viewpoint, there are other two essential directions to be considered. The direction towards which a point P faces is called its *facing direction*, denoted by $\vec{p}$. The vector $\overrightarrow{PS}$ is called *viewed direction* of the object, which reflects the viewpoint of sensor S. Figure 1 illustrates these directions which will be useful in subsequent discussion.

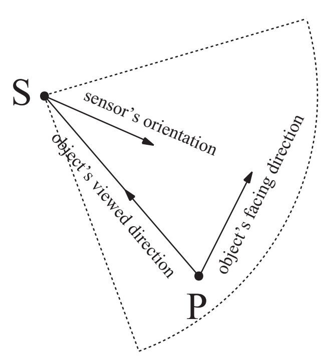

Figure 1: For sensor S and point P, the orientation, viewed direction and facing direction are depicted respectively.

We consider heterogeneous sensors similar to [23]. To describe sensors of different qualities, we partition sensors to u groups $G_1, G_2, \cdots, G_u$, where u is a constant. As the total number of sensors is n, each group $G_y (y = 1, 2, \cdots, u)$ has $n_y = c_y n$ sensors, where c_y is a constant invariant to n. Clearly, c_y satisfies $0 < c_y < 1$ and $\sum_{y=1}^{u} c_y = 1$. All sensors in group G_y own identical sensing radius r_y and angle ϕ_y, but either $r_y \neq r_z$ or $\phi_y \neq \phi_z$ will hold if $y \neq z (y, z = 1, 2, \cdots, u)$. We mainly study the asymptotic coverage here, implying that n is a variable approaching to infinity, whereas r_y and ϕ_y are dependent variables of n, sometimes denoted by $r_y(n)$ and $\phi_y(n)$. When the total number of sensors n changes, the requirements for $r_y(n)$ and $\phi_y(n)$ should change along with n.

2.2 Static and Mobility Patterns

For mobility patterns, we divide the sensing process into time slots with unit length, and sensors can move according to certain mobility patterns in each time slot. When assuming the network works in a large amount of time slots, a single time slot can also be viewed as an instant.

- **Static Model**: Wherever a sensor locates, its orientation $\vec{f}$ faces towards all possible directions with equal probability. And once a sensor is deployed, neither its orientation $\vec{f}$ nor its location will change, which means that the camera would not steer its lens during the operation.

- **2-Dimensional Random Walk Mobility Model**: At the very beginning of each time slot, each sensor uniformly chooses a random direction $\sigma \in [0, 2\pi)$, and then it rotates its facing direction to the chosen one and moves along the direction with a constant velocity v in each time slot and the velocity is $\Theta(1)$.

- **1-Dimensional Random Walk Mobility Model**: Sensors are classified into two types of equal quantity, H-nodes and V-nodes. And sensors of each type move horizontally and vertically, respectively. At the very beginning of each time slot, each sensor randomly and uniformly chooses a direction along its moving dimension and travels in the selected direction for a certain distance D, a random variable uniformly distributed from 0 to 1.[†]

[†]Long distance travel is energy-consuming. And if the sensor can travel beyond the dimension of the operational region (i.e., $D > 1$), it can always cover the area along its moving dimension which is meaningless.

Note that the results can be easily expanded to more general case that D follows a certain distribution function $f_D(d)$ and we omit it here as well. The velocity of the sensors is not considered, as long as they could reach the destination within the time slot, and remain stationary until the next slot.

- **Random Rotating Mobility Model**: Cameras can rotate and change their orientation clockwise or counterclockwise. At the very beginning of each time slot, each sensor randomly chooses a rotating direction, i.e. clockwise or counterclockwise, and then rotates an angle Ψ, a random variable uniformly distributed between 0 and 2π. Note that the results can be easily expanded to more general case that Ψ follows a certain distribution function $f_\Psi(\psi)$. For brevity, we omit it here. Similarly, the velocity of sensors is ignored.

The static model is widely used [2], since it can provide intuitions and characterize the upper or lower bound. And in some literatures, it is called I.I.D. mobility pattern. Since I.I.D mobility model makes no change on how much area the sensor covers, intuitively we could take I.I.D. mobility model as quasi-static model, or view static model as I.I.D. mobility model with an infinity period. The 2-dimensional random walk mobility model can highly exploit the randomness of the motion of the nodes and is suitable to depict realistic situation that the statistics about the habit of moving platforms is unknown. The 1-dimensional random walk mobility model is motivated by certain networks that nodes move along determined tracks such as the networks employed in streets, systems consisted of satellites moving in fixed orbits etc. The random rotation mobility model is a new concept we propose, which characterizes camera sensors that can rotate their orientation to broaden viewing angle.

2.3 Performance Measures

To assess the full view coverage performance in CSNs, the following five definitions are proposed.

2.3.1 Definition of θ-view coverage

For a specific facing direction $\vec{p}$ of point P, it achieves θ-view coverage if it is covered by at least one sensor and the angle between $\vec{p}$ and its viewed direction is no more than θ. Here, $\theta \in (0, \pi]$ is a predefined constant parameter called effective angle.

2.3.2 Definition of Full View Coverage

For a point P, it is full view covered if every possible facing direction $\vec{p}$ of it is θ-view covered. The operational region achieves full view coverage iff every point in it achieve full view coverage.

2.3.3 Definition of Full View Coverage in a period T

If during a time period T (T time slots), the network achieves full view coverage for at least one time slot, we say the network achieves full view coverage in period T.

2.3.4 Definition of an event A_n with high probability (w.h.p)

If event A_n satisfy $lim_{n\to\infty}P(A_n) = 1$, then event A_n will happen with high probability.

2.3.5 Definition of an event A_n almost sure (a.s.)

Let A_n be a countable collection of sets, and $\limsup_{n\to\infty} A_n = \bigcap_{n=1}^{\infty} \bigcup_{m\geq n} A_m$, which means that for every element in the limsup, for every N, there exists an A_n with $n \geq N$ that has the element. For event A_n, if $\mathbb{P}(\limsup_{n\to\infty} A_n) = 1$, we say the event A_n will almost surely happen or happen infinitely often.

2.3.6 Definition of Equivalent Sensing Radius

For heterogeneous camera sensor networks, we define the equivalent sensing radius (ESR) for each static and mobility pattern to analyze the asymptotic full view coverage. The ESR of the heterogeneity CSN for static model is $r = \sqrt{\sum_{y=1}^{u} c_y \frac{\phi_y}{2\pi} r_y^2}$, the ESR for 2-dimensional random walk mobility model or 1-dimensional random walk mobility model is $r_i = \sum_{y=1}^{u} c_y \frac{\phi_y}{2\pi} r_y, i = 2.r.w., 1.r.w.$, and the ESR for random rotating mobility model is $r = \sqrt{\sum_{y=1}^{u} c_y (2 - (1 - \frac{\phi_y}{2\pi})^2) r_y^2}$.

In this part, $\frac{\phi_y}{2\pi}$ is viewed as the weight of each sensor's radius. When $\phi = 2\pi$, it is equivalent to a sensor whose sensing range is a circle, and ESR in this case is the same as the ESR for omnidirectional sensors in [23].

2.3.7 Definition of Critical ESR

Let $\mathcal{H}$ denotes the event that the operational region is full view covered. Then if

$$\lim_{n\to\infty} P(\mathcal{H}) = 1, \text{if } r_i \geq cR_i(n) \text{ for any } c > 1;$$
$$\lim_{n\to\infty} P(\mathcal{H}) < 1, \text{if } r_i \leq \hat{c}R_i(n) \text{ for any } 0 < \hat{c} < 1,$$

where $R_i(n)$ is the critical ESR under four different static and mobile patterns, and $i = stat, r.r., 2.r.w., 1.r.u$

3 Main Result

- With static model, the equivalent sensing radius (ESR) is

$$R(n) = \sqrt{\frac{2(\log n + \log\log n)}{n\theta}}.$$

- With 2-dimensional random walk mobility model, the ESR is

$$R(n) = \begin{cases} \frac{\log n + \log\log n}{2nTv\sin\theta} & \text{if } \theta < \frac{\pi}{2} \\ \frac{\log n + \log\log n}{2nTv} & \text{if } \theta \geq \frac{\pi}{2} \end{cases}$$

- With 1-dimensional random walk mobility model, the ESR is

$$R(n) = \frac{3\pi(\log n + \log\log n)}{2\theta n}.$$

- With random rotating mobility model, the ESR is

$$R(n) = \sqrt{\frac{4(\log n + \log(\log n))}{n\theta}}.$$

4 Overview of the Geometric Analysis and Preliminaries

In [23], Wang proves that, the full coverage of a $\sqrt{m} \times \sqrt{m}$ dense grid $\mathbb{M}$ can promise the full coverage of the unit square, when $m = n\log n$, based on Theorem 4.1 in [2]. We can also prove that the θ-view coverage of a facing direction set $\mathbb{K}$ formed by k directions of a point can promise its full view coverage when $k = n\log n$, and we derive the following useful results. Figure 2 (b) illustrates an example of facing direction set $\mathbb{K}$ of point P when $k = 8$.

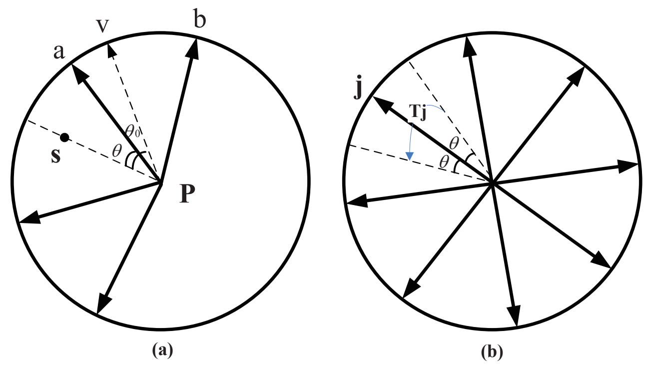

Figure 2: (a) shows a set of four nearest directions include a and b in the direction set $\mathbb{K}$, (b) shows the possible area T_j to θ-view cover orientation O_j.

Lemma 1 *Assume θ, θ_0, k are constraints and $\theta_0 = \theta + \frac{2\pi}{k}$. $\mathbb{K}$ is a facing direction set formed by k directions uniformly distributed around point P. If these k directions can all achieve θ-view coverage, then point P can achieve full view coverage with effective angle θ_0.*

Proof: Let v be an arbitrary facing direction of point P. Without loss of generality, we assume it is inside the sector formed by virtual orientation a and b in $\mathbb{K}$ and is closest to orientation a, as shown in Figure 2 (a). By assumption, there exists at least one sensor that can cover a, with effective angle θ. Suppose one of them locates at point s (in Figure 2 (a)), and $\angle(s, a) < \theta$. s also represents the viewed direction without confusion. Besides $\angle(a, v) < \frac{2\pi}{k}$, then

$$\angle(s, v) = \angle(s, a) + \angle(a, v) < \theta + \frac{2\pi}{k} = \theta_0. \tag{1}$$

Obviously Eq. (1) still holds when the sensor locates between a and b. Also $\lim_{k\to\infty} \theta_0 = \theta$, which means θ_0 is only slightly larger than θ, when k is large enough. With Theorem 4.1 in [2], the following theorem is derived.

Theorem 1 *For point P, if a k facing direction set $\mathbb{K}$ satisfying $k = n \log n$, the θ-view coverage of set $\mathbb{K}$ can promise the full view coverage of P with effective angle θ when n is large enough.*

Thus we can focus on the θ-view coverage of orientation set $\mathbb{K}$ for the dense gird $\mathbb{M}$ to estimate full view coverage performance of the operational region.

5 the Critical Sensing Range for Static Camera Sensor Networks

In this section, we mainly focus on the full view coverage for static camera sensor networks under uniform deployment, and obtain the equivalent sensing range for heterogeneous cameras. We first analyze the equivalent sensing range for dense grid $\mathbb{M}$, then expand it to case of the whole area and derive the following theorem.

Theorem 2 *Under the uniform deployment with static model, the critical ESR for mobile heterogeneous CSNs to achieve asymptotic full view coverage is*

$$R_{stat}(n) = \sqrt{\frac{2(\log n + \log\log n)}{n\theta}}.$$

Let $\mathbb{P}_{i,j,S_y}$ denote the probability that orientation O_j of point P_i is θ-viewed covered by sensor S in group G_y. To make O_j of set $\mathbb{K}$ θ-viewed covered, at least one sensor should locate in sector T_j, as shown in Figure 2 (b). For sector T_j, the angular bisector is orientation j, with an angle 2θ. Then

$$\begin{aligned}\mathbb{P}_{i,j,S_y} &= \mathbb{P}(S\ falls\ in\ T_j) \times \mathbb{P}(S \text{ has proper orientation}) \\ &= \frac{2\theta}{2\pi} \times \pi r_y^2(n) \times \frac{\phi_y}{2\pi} \\ &= \frac{r_y^2(n)\phi_y\theta}{2\pi}\end{aligned}$$

5.1 Necessary Condition of Theorem 2

Let $\mathcal{G}_{rw}(n, r(n))$ denote the network that each point in $\mathbb{M}$ achieves full view coverage when the sensing range is $r(n)$, and we use $P_{f-rw}(n, r(n))$ to represent the probability that $\mathcal{G}_{rw}(n, r(n))$ has at least one point that is not full view covered. Then we derive the following proposition. For simplicity, we say a direction uncovered and not θ-view covered equivalently, and a point uncovered and not full view covered interchangeably.

Proposition 1 *In the static heterogeneous CSN, if*

$$r_{stat}(n) = \sqrt{\frac{2(\log n + \log\log n + \omega(n))}{n\theta}},$$

$m = n\log n$ and $k = n\log n$, then

$$\liminf_{n\to\infty} P_{f-rw}(n, r(n)) \geq e^{-2\omega} - \frac{\theta}{\pi}e^{-3\omega},$$

where $\omega = \lim_{n\to\infty}\omega(n)$.

proof: To ease the complexity of the proof, we provide the following lemma first.

Lemma 2 *Given a variable $x = x(n)$ satisfies $0 < x(n) < \frac{1}{2}$, and a variable $y = y(n) > 0$, then $(1-x)^y \sim e^{-xy}$ if x^2y approaches to zero as $n \to +\infty$.*

Using method similar to the proof of LEMMA 1 in [13], we could easily prove Lemma 2. Then we study the case that $r(n) = \sqrt{\frac{2(\log n + \log\log n + \omega(n))}{n\theta}}$ for a fixed ω. Referring to Bonferroni inequalities, we get

$$\begin{aligned}
&P_{f-rw}(n, r(n)) \\
&\geq \sum_{P_i\in\mathbb{M}} \mathbb{P}(\{\text{some point } P_i \text{ is not full view covered}\}) \\
&\geq \sum_{P_i\in\mathbb{M}} \mathbb{P}(\{P_i \text{ is the only uncovered point}\}) \\
&\geq \sum_{P_i\in\mathbb{M}}\sum_{O_j\in\mathbb{K}} \mathbb{P}(\{\text{only } O_j \text{ of } P_i \text{ is uncovered}\}) \\
&\geq \sum_{P_i\in\mathbb{M}}\sum_{O_j\in\mathbb{K}} \mathbb{P}(\{O_j \text{ of } P_i \text{ is uncovered}\}) \\
&- \sum_{P_i\in\mathbb{M}}\sum_{O_j,O_h\in\mathbb{K}}^{O_j\neq O_h} \mathbb{P}(\{\ O_j \text{ and } O_h \text{ of } P_i \text{ are uncovered}\}).
\end{aligned} \tag{2}$$

For the first term of the R.H.S. of Eq. (2)

$$\begin{aligned}
&\mathbb{P}(\{O_j \text{ of } P_i \text{ is uncovered}\}) \\
&\geq \prod_{y=1}^{u} \mathbb{P}(\{O_j \text{ is uncovered by sensors in } G_y\}) \\
&= \prod_{y=1}^{u} (1 - \frac{r_y^2(n)\phi_y\theta}{2\pi})^{c_y n},
\end{aligned} \tag{3}$$

where $\frac{r_y^2(n)\phi_y\theta}{2\pi}$ represents the probability that orientation O_j of point P_i is θ-viewed covered by sensor S in group G_y, while $c_y n$ represents the number of sensors in group G_y.

Then with Lemma (2) and Eq. (3), we obtain that

$$\begin{aligned}
&\sum_{P_i\in\mathbb{M}}\sum_{O_j\in\mathbb{K}}\mathbb{P}(\{O_j \text{ of } P_i \text{ are uncovered}) \\
&\quad \geq mk\prod_{y=1}^{u}(1-\frac{r_y^2(n)\phi_y\theta}{2\pi})^{c_y n} \\
&\quad \sim mke^{-n\theta\sum_{y=1}^{u}c_y\frac{\phi_y}{2\pi}r_y^2(n)} \\
&\quad = mke^{-n\theta r_{stat}^2(n)} \\
&\quad = (n\log n)^2e^{-2(\log n+\log\log n+\omega)} \\
&\quad = e^{-2\omega}.
\end{aligned} \tag{4}$$

For the second term of the R.H.S. of Eq. (2)

$$\begin{aligned}
&\mathbb{P}(\{O_j \text{ and } O_h \text{ of } P_i \text{ is uncovered}\}) \\
&\leq \frac{2\theta}{2\pi}\prod_{y=1}^{u}(1-\frac{3}{2}\frac{r_y^2(n)\phi_y\theta}{2\pi})^{c_y n} \\
&+(1-\frac{2\theta}{2\pi})\prod_{y=1}^{u}(1-2\frac{r_y^2(n)\phi_y\theta}{2\pi})^{c_y n},
\end{aligned} \tag{5}$$

where the two terms on the right side correspond to the cases when $\angle(O_j, O_h) \leq 2\theta$ and $\angle(O_j, O_h) > 2\theta$. For the first term, $\frac{3}{2}\frac{r_y^2(n)\phi_y\theta}{2\pi}$ is the average area sensors might locate to θ-view cover O_j or O_h. Since the overlapping area between O_j and O_h is a random variable, uniformly distributed between 0 and $\theta r^2(n)$, the corresponding possible area is also a random variable, uniformly distributed between $\frac{r_y^2(n)\phi_y\theta}{2\pi}$ and $2\frac{r_y^2(n)\phi_y\theta}{2\pi}$, so that its expectation is $\frac{3}{2}\frac{r_y^2(n)\phi_y\theta}{2\pi}$. We can analyze the second term similarly.

Then with Lemma (2) and Eq. (5), we obtain that

$$\begin{aligned}
&\sum_{P_i\in\mathbb{M}}\sum_{O_j,O_h\in\mathbb{K}}^{O_j\neq O_h}\mathbb{P}(\{O_j \text{ and } O_h \text{ of } P_i \text{ is uncovered})\\
&\leq mk^2\frac{2\theta}{2\pi}\prod_{y=1}^{u}(1-\frac{3}{2}\frac{r_y^2(n)\phi_y\theta}{2\pi})^{c_y n}\\
&+mk^2(1-\frac{2\theta}{2\pi})\prod_{y=1}^{u}(1-2\frac{r_y^2(n)\phi_y\theta}{2\pi})^{c_y n}\\
&\sim mk^2\frac{\theta}{\pi}e^{-\frac{3n\theta}{2}\sum_{y=1}^{u}c_y\frac{\phi_y}{2\pi}r_y^2(n)}\\
&+mk^2(1-\frac{\theta}{\pi})e^{-2n\theta\sum_{y=1}^{u}c_y\frac{\phi_y}{2\pi}r_y^2(n)}\\
&=mk^2\frac{\theta}{\pi}e^{-\frac{3n\theta}{2}r_{stat}^2}+mk^2(1-\frac{\theta}{\pi})e^{-2n\theta r_{stat}^2}\\
&=\frac{\theta}{\pi}e^{-3\omega}+(1-\frac{\theta}{\pi})e^{-4\omega}\frac{1}{n\log n}.
\end{aligned} \tag{6}$$

Since we consider the asymptotic coverage problem, which means that the total number of cameras n approaches to infinity. Then for any fixed ω, we obtain that

$$\liminf_{n\to\infty} P_{f-rw}(n,r(n)) \geq e^{-2\omega}-\frac{\theta}{\pi}e^{-3\omega}.$$

Now we consider the case when ω is a function of n with $\omega=\lim_{n\to\infty}\omega(n)$, which indicates that $\omega(n)<\omega+\delta$ for any $\delta>0$, for all $n>N_\delta$. Since $P_{f-rw}(n,r(n))$ is monotonously decreasing in r_{stat} and thus in ω, we have

$$\liminf_{n\to\infty} P_{f-rw}(n,r(n)) \geq e^{-2(\omega+\delta)}-\frac{\theta}{\pi}e^{-3(\omega+\delta)}, \tag{7}$$

for all $n>N_\delta$.

From Proposition 1, we know that $P_{f-rw}(n,r(n))$ is bounded away from zero. Combined with the definition of ESR for static model, we know that $R_{stat}\geq\sqrt{\frac{2(\log n+\log(\log n))}{n\theta}}$ is necessary to achieve the full view coverage of $\mathbb{M}$.

Moreover, if sensing range is less than $\sqrt{\frac{3}{2}}$ of ESR of static model, we could extend our result to the following Theorem.

Theorem 3 *Under the uniform deployment with static model, if the CSN satisfy*

$$r(n)<\sqrt{\frac{3}{2}}R_{stat},$$

then it is necessary for the network to achieve almost surely coverage.

proof: We denote the event that the operational region with n camera sensors has at least one point that is not full view covered as $\widehat{\mathcal{H}_n}$, and use $\mathbb{P}(\widehat{\mathcal{H}_n})$ to represent the corresponding probability.

Assuming $r(n) = c\sqrt{\frac{3}{2}}R_{stat}$, and referring to Bonferroni inequalities, we get

$$
\begin{aligned}
&\mathbb{P}(\widehat{\mathcal{H}_n}) \\
&\geq \sum_{P_i \in \mathbb{M}} \sum_{O_j \in \mathbb{K}} \mathbb{P}(\{O_j \text{ of } P_i \text{ is uncovered}\}) - \sum_{P_i \in \mathbb{M}} \sum_{O_j, O_h \in \mathbb{K}}^{O_j \neq O_h} \mathbb{P}(\{\ O_j \text{ and } O_h \text{ of } P_i \text{ are uncovered}\}) \\
&= mk \prod_{y=1}^{u} (1 - \frac{r_y^2(n)\phi_y\theta}{2\pi})^{c_y n} - mk^2 \frac{2\theta}{2\pi} \prod_{y=1}^{u} (1 - \frac{3}{2}\frac{r_y^2(n)\phi_y\theta}{2\pi})^{c_y n} - mk^2(1 - \frac{2\theta}{2\pi}) \prod_{y=1}^{u} (1 - 2\frac{r_y^2(n)\phi_y\theta}{2\pi})^{c_y n} \\
&\sim mke^{-n\theta \sum_{y=1}^{u} c_y \frac{\phi_y}{2\pi} r_y^2(n)} - mk^2 \frac{\theta}{\pi} e^{-\frac{3n\theta}{2} \sum_{y=1}^{u} c_y \frac{\phi_y}{2\pi} r_y^2(n)} - mk^2(1 - \frac{\theta}{\pi}) e^{-2n\theta \sum_{y=1}^{u} c_y \frac{\phi_y}{2\pi} r_y^2(n)} \\
&= mke^{-n\theta (c\sqrt{\frac{3}{2}}R_{stat})^2} - mk^2 \frac{\theta}{\pi} e^{-\frac{3n\theta}{2}(c\sqrt{\frac{3}{2}}R_{stat})^2} + mk^2(1 - \frac{\theta}{\pi}) e^{-2n\theta (c\sqrt{\frac{3}{2}}R_{stat})^2} \\
&= \frac{1}{(n\log n)^{3c^2-2}} - \frac{\theta}{\pi}\frac{1}{(n\log n)^{\frac{9}{2}c^2-3}} - (1 - \frac{\theta}{\pi})\frac{1}{(n\log n)^{6c^2-3}}.
\end{aligned}
\tag{8}
$$

If $r(n)$ is smaller than $\sqrt{\frac{3}{2}}R_{stat}$, namely, $c < 1$, then according to the characteristic of P-series, we know that

$$
\sum_{n=1}^{\infty} \mathbb{P}(\widehat{\mathcal{H}_n}) > \sum_{n=1}^{\infty} \frac{1}{(n\log n)^{3c^2-2}} - \sum_{n=1}^{\infty} \frac{\theta}{\pi} \frac{1}{(n\log n)^{\frac{9}{2}c^2-3}} - \sum_{n=1}^{\infty} (1 - \frac{\theta}{\pi}) \frac{1}{(n\log n)^{6c^2-3}} > \infty.
$$

And $\{\widehat{\mathcal{H}_n}\}$ is a sequence of independence events. Then using *Borel Cantelli Lemma* in [27], we know that

$$
\mathbb{P}(\limsup_{n\to\infty} \widehat{\mathcal{H}_n}) = 1,
$$

which means the event $\widehat{\mathcal{H}_n}$ will infinitely often happen under asymptotic network. Namely, the network is almost surely uncovered when $r(n)$ is smaller than $\sqrt{\frac{3}{2}}R_{stat}$.

5.2 Sufficient Condition of Theorem 2

First, we obtain the following proposition.

Proposition 2 *In CSN, if n sensors are randomly and uniformly deployed in a unit square, and $r_{stat} = cR_{stat}(n)$ where $c > 1$, then*

$$\liminf_{n\to\infty} \mathbb{P}(\widehat{\mathcal{H}}) = 0. \tag{9}$$

where $\widehat{\mathcal{H}}$ denotes the event that the operational region is not full view covered as defined in Section 2.

proof: We suppose that $r = cR_{stat}(n)$ where $c > 1$, and use F_i to denote the event that a point P_i is not full view covered, $F_{i,j}$ to denote that O_j of P_i is not θ-view covered. Then, it suffices to prove that

$$\lim_{n\to\infty} P\left(\bigcup_{i=1}^{m} F_i\right) = 0.$$

Deriving its upper bound, we have

$$P\left(\bigcup_{i=1}^{m} F_i\right) \leq \sum_{i=1}^{m} P(F_i) \leq \sum_{i=1}^{m}\sum_{j=1}^{k} P(F_{i,j}). \tag{10}$$

We use similar method in the necessary condition part to calculate $P(F_{i,j})$ as follows

$$\begin{aligned}
\mathbb{P}(\widehat{\mathcal{H}}) &= \mathbb{P}(\bigcup_{i=1}^{m} \mathcal{F}_i) \\
&\leq (n\log n)^2 \prod_{y=1}^{u} (1 - \frac{r_y^2 \phi_y \theta}{2\pi})^{c_y n} \\
&\sim (n\log n)^2 e^{-n\theta (r_{stat})^2} \\
&= \frac{1}{(n\log n)^{2c^2-2}} \to 0,
\end{aligned} \tag{11}$$

for any $c > 1$.

Then from Proposition 2 and the definition of critical ESR for static model, we know that $R_{stat} \geq \sqrt{\frac{2(\log n + \log(\log n))}{n\theta}}$ is sufficient to achieve the full view coverage of $\mathbb{M}$.

Moreover, if sensing range is more than $\sqrt{\frac{3}{2}}$ of ESR of static model, we could extend our result to the following Theorem.

Theorem 4 *Under the uniform deployment with static model, if the CSN satisfy*

$$r(n) > \sqrt{\frac{3}{2}} R_{stat},$$

then it is sufficient for the network to achieve almost surely coverage.

proof: We denote the event that the operational region is not full view covered with n camera sensors as $\widehat{\mathcal{H}_n}$. According to the analysis above, we know that the probability that event $\widehat{\mathcal{H}_n}$ happens satisfy

$$\mathbb{P}(\widehat{\mathcal{H}_n}) \leq \frac{1}{(n \log n)^{2c^2-2}}.$$

And if $r(n)$ is larger than $\sqrt{\frac{3}{2}}R_{stat}$, namely, $c > \sqrt{\frac{3}{2}}$, then according to the characteristic of P-series, we know that

$$\sum_{n=1}^{\infty} \mathbb{P}(\widehat{\mathcal{H}_n}) \leq \sum_{n=1}^{\infty} \frac{1}{(n \log n)^{2c^2-2}} < \infty.$$

Then using *Borel Cantelli Lemma* in [27], we know that

$$\mathbb{P}(\limsup_{n\to\infty} \widehat{\mathcal{H}_n}) = 0,$$

which means the event $\widehat{\mathcal{H}_n}$ will not infinitely often happen under asymptotic network. Namely, the network is a.s. covered as long as $r(n)$ is large enough.

5.3 Critical ESR for Full View Coverage of the Operational Range

Until now we have already proved that $R_{stat} \geq \sqrt{\frac{2(\log n+\log(\log n))}{n\theta}}$ is the critical condition to achieve full view coverage for dense grid $\mathbb{M}$. Referring to Lemma 3.1 in [2], as well as Lemma 1 and Theorem 1 in this paper and using similar approach as Theorem 4.1 in [2], the density of the dense grid $m = n \log n$ and the density of the orientation set $k = n \log n$ are sufficiently large to evaluate the full view coverage of the whole area. Therefore, Theorem 2 follows.

6 the Critical Sensing Range for Mobile Camera Sensor Networks

In this section, we investigate full view coverage problem for camera sensor networks under uniform deployment under three different mobile patterns, namely, 2-dimensional random walk mobility model, 1-dimensional random walk mobility model and random rotating mobility model.

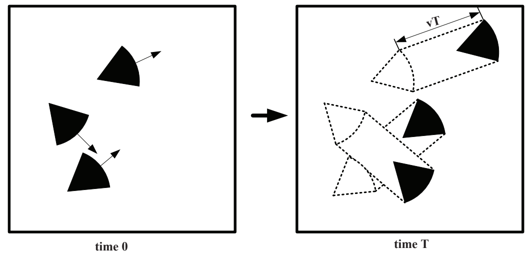

Figure 3: Full view coverage of CSNs under 2-dimensional random walk: the left figure depicts the initial network configuration at time 0 and the right illustrates the effect of sensor mobility during time interval [0, T). The solid disks constitute the area being covered at the given time instant, and the union of the region inside the dotted line and the solid disks represents the area being covered during the time interval

6.1 Critical ESR Under 2-Dimensional Random Walk Mobility Model

We investigate full view coverage in one time slot under 2-Dimensional Random Walk Mobility Model, and Figure 3 illustrates the effect of random walk mobility of the sensor on area coverage. We will first analyze full view coverage for dense grid $\mathbb{M}$, and then expand it to the whole area.

Theorem 5 *Under the uniform deployment with 2-dimensional random walk mobility model, the critical ESR for mobile heterogeneous CSNs to achieve asymptotic full view coverage is*

$$R_{2.r.w}(n) = \begin{cases} \frac{\log n + \log\log n}{2nTv\sin\theta} & \text{if } \theta < \frac{\pi}{2} \\ \frac{\log n + \log\log n}{2nTv} & \text{if } \theta \geq \frac{\pi}{2} \end{cases} .$$

We will mainly focus on the condition that $\theta < \frac{\pi}{2}$, and it is similar when $\theta \geq \frac{\pi}{2}$.

6.1.1 Failure Probability of an Orientation in $\mathbb{K}$

Let $\mathcal{F}_{i,j}$ denote the event that orientation O_j of point P_i is not θ-viewed covered during the time slot τ, and $\mathbb{P}(\mathcal{F}_{i,j})$ denote the corresponding probability. We use $\mathbb{P}_{i,j,S_y}$ to represent that O_j of point P_i is θ-viewed covered by sensor S in group G_y. Then we obtain

$$\mathbb{P}_{i,j,S_y} = ((\theta + \alpha)r_y^2(n) + 2vTr_y(n)sin\theta)\frac{\phi_y}{2\pi}, \tag{12}$$

In the above equation, $(\theta+\alpha)r_y^2(n)+2vTr_y(n)sin\theta$ represents the possible area the sensor may locate in order to θ-view cover O_j during T slots, if it does not change its direction during the process. In this formula $\theta r_y^2(n)$ represents the possible area where sensors in group $G_y, y=1,2,..,u$ might locate if it is stationary,like sector T_j in Figure 2. $\alpha r_y^2(n)$ represents the additional area due to rotation. Considering its mobility character, the possible area can be $2vTr_y(n)sin\theta$ more, like the region inside the dotted line in Figure 3. If the sensor changes its direction during this period, the sensing area will overlap, making it no larger than $2vTr_y(n)sin\theta$. For formula $\frac{\phi_y}{2\pi}$, it represents the probability that the sensor in group G_y has proper orientation to sense the point.

Then, $\mathbb{P}(\mathcal{F}_{i,j})$ can be easily calculated.

6.1.2 Necessary ESR for Full View Coverage of the Dense Grid

Here, we use $\widehat{\mathcal{H}^\tau}$ denote the event that the dense grid $\mathbb{M}$ is not fully full view covered in the time slot τ, and present the following proposition regarding the necessary condition.

Proposition 3 *In the mobile heterogeneous CSN with 2-dimensional random walk mobility model, if* $r_{2.r.w.}=\frac{\log n+\log\log n+\xi(n)}{2nTv\sin\theta}$ *and the density of the dense grid* $\mathbb{M}$ *is* $m=n\log n$*, the density of the orientation set* $\mathbb{K}$ *is* $k=n\log n$*, then*

$$\liminf_{n\to\infty}\mathbb{P}_\tau(\widehat{\mathcal{H}^\tau})\geq e^{-2\xi}-\frac{\theta}{\pi}e^{-3\xi},$$

where $\xi=\lim_{n\to\infty}\xi(n)$*.*

proof: Similarly to the proof of Proposition 1, we first study the case where $r_{2.r.w.}=\frac{\log n+\log\log n+\xi}{2nTv\sin\theta}$, for a fix ξ.

$$\begin{aligned}\mathbb{P}_\tau(\widehat{\mathcal{H}^\tau})\geq&\sum_{P_i\in\mathbb{M}}\sum_{O_j\in\mathbb{K}}\mathbb{P}_\tau(\{O_j\text{ of }P_i\text{ is uncovered}\})\\&-\sum_{P_i\in\mathbb{M}}\sum_{\substack{O_j\neq O_h\\O_j,O_h\in\mathbb{K}}}\mathbb{P}_\tau(\{O_j\text{ and }O_h\text{ of }P_i\text{ are uncovered}).\end{aligned}\tag{13}$$

And we calculate that

$$\begin{aligned}&\mathbb{P}_\tau(\{O_j\ of\ P_i\ is\ uncovered\})\\=&\prod_{y=1}^{u}(1-((\theta+\alpha)r_y^2(n)+2vTr_y(n)sin\theta)\frac{\phi_y}{2\pi})^{c_y n}\\=&\prod_{y=1}^{u}(1-(1+\lambda_y)\frac{\phi_y vTr_y(n)sin\theta}{\pi})^{c_y n},\end{aligned}$$

where $\lambda_y = \frac{(\theta+\alpha)r_y(n)}{2vTsin\theta} = \Theta(r_y(n)) = o(1)$, since the asymptotic coverage problem is considered.

Then we could bound the first term of R.H.S of Eq. (13),

$$\begin{aligned}&\sum_{P_i\in\mathbb{M}}\sum_{O_j\in\mathbb{K}}\mathbb{P}_\tau(\{O_j\ of\ P_i\ is\ uncovered\})\\&\geq mke^{-4vTsin\theta n}\sum_{y=1}^{u}c_y\frac{\phi_y}{2\pi}r_y\\&=mke^{-4vTsin\theta nr_{2.r.w.}}\\&=e^{-2\xi}.\end{aligned} \tag{14}$$

Similarly, we bound the second term

$$\sum_{P_i\in\mathbb{M}}\sum_{O_j,O_h\in\mathbb{K}}^{O_j\neq O_h}\mathbb{P}_\tau(\{O_j \text{ and } O_h \text{ of } P_i \text{ are uncovered}) \sim \frac{\theta}{\pi}e^{-3\xi}. \tag{15}$$

Then we have

$$\liminf_{n\to\infty}\mathbb{P}_\tau(\widehat{\mathcal{H}^\tau}) \geq e^{-2\xi} - \frac{\theta}{\pi}e^{-3\xi}, \tag{16}$$

Taking into account that ξ is a function of n, the conclusion still holds.

According to Proposition 8, we know that $R_{2.r.w.} \geq \frac{\log n+\log\log n+\xi(n)}{2nTv\sin\theta}$ is necessary to achieve the full view coverage of $\mathbb{M}$.

Moreover, if sensing range is less than $\sqrt{\frac{3}{2}}$ of ESR of the 2-dimensional random walk mobility model, we could extend our result to the following Theorem.

Theorem 6 *Under the uniform deployment with the 2-dimensional random walk mobility model, if the CSN satisfy*

$$r(n) < \sqrt{\frac{3}{2}}R_{2.r.w.},$$

then it is necessary for the network to achieve almost surely coverage.

proof: Using similar method as the proof of Theorem 3, we could easily prove Theorem 6.

6.1.3 Sufficient ESR for Full View Coverage of the Dense Grid

First, we obtain the following proposition.

Proposition 4 *In CSN, if n sensors are randomly and uniformly deployed in a unit square, and $r_{2.r.w.} = cR_{2.r.w.}(n)$ where $c > 1$, then*

$$\liminf_{n\to\infty} \mathbb{P}_\tau(\widehat{\mathcal{H}_\tau}) = 0. \tag{17}$$

proof: Using similar approach as Proposition 2, we can proof this proposition.

$$\begin{aligned}
\mathbb{P}_\tau(\widehat{\mathcal{H}_\tau}) &= \mathbb{P}_\tau(\bigcup_{i=1}^{m} \mathcal{F}_i) \\
&\le mk \prod_{y=1}^{u} (1-((\theta+\alpha)r_y^2(n) + 2vTr_y(n)sin\theta)\frac{\phi_y}{2\pi})^{c_y n} \\
&\sim (n\log n)^2 e^{-4vTsin\theta n r_{2.r.w.}} \\
&= \frac{1}{(n\log n)^{2c^2-2}} \to 0,
\end{aligned} \tag{18}$$

for any $c > 1$.

From Proposition 4 and the definition of critical ESR for 2-dimensional random walk mobility model, we know that $R_{2.r.w.} \ge \frac{\log n + \log\log n + \xi(n)}{2nTv\sin\theta}$ is sufficient to achieve the full view coverage of $\mathbb{M}$.

Moreover, if sensing range is more than $\sqrt{\frac{3}{2}}$ of ESR of the 2-dimensional random walk mobility model, we could extend our result to the following Theorem.

Theorem 7 *Under the uniform deployment with 2-dimensional random walk mobility model, if the CSN satisfy*

$$r(n) > \sqrt{\frac{3}{2}} R_{2.r.w.},$$

then it is sufficient for the network to achieve almost surely coverage.

proof: Using similar method as the proof of Theorem 4, we could easily prove Theorem 7.

6.1.4 Critical ESR for Full View Coverage of the Operational Range

Similar to the analysis in the static model, Theorem 5 follows.

6.2 Critical ESR Under 1-Dimensional Random Walk Mobility Model

6.2.1 Failure Probability of an Orientation in $\mathbb{K}$

Similarly, let $\mathcal{F}_{i,j}$ denote the event that orientation O_j of point P_i is not θ-viewed covered during the time slot τ, and $\mathbb{P}(\mathcal{F}_{i,j})$ denote the corresponding probability. We use $\mathbb{P}_{i,j,S_y}$ to represent that O_j of point P_i is θ-viewed covered by sensor S in group G_y.

From Wang in [23], we know that for 1-dimensional random walk mobility model, the probability that S falls in the circle around of P_i, with radius r_y is $\mathbb{P}_{i,S} = \frac{4}{3}r_y$. Clearly $\mathbb{P}(S\ falls\ in\ cirle\ around\ P_i) = \mathbb{P}_{i,S}$. Then we obtain

$$\begin{aligned}
\mathbb{P}_{i,j,S_y} &= \mathbb{P}(\text{S falls in } T_j) \times \mathbb{P}(\text{S has proper orientation}) \\
&= \mathbb{P}(\text{S falls in the cirle around } P_i) \times \frac{2\theta}{2\pi} \times \frac{\phi_y}{2\pi} \\
&= \frac{\theta\phi_y}{2\pi^2}\mathbb{P}_{i,S} \\
&= \frac{2\theta\phi_y r_y(n)}{3\pi^2}.
\end{aligned} \tag{19}$$

Then, $\mathbb{P}(\mathcal{F}_{i,j})$ can be easily calculated.

6.2.2 Necessary ESR for Full View Coverage of the Dense Grid

Here, we use $\widehat{\mathcal{H}^{\tau}}$ denote the event that the dense grid $\mathbb{M}$ is not fully full view covered in the time slot τ, and have the following technical lemma.

Lemma 3 *If* $r_{1.r.w.} = \frac{3\pi(\log n+\log\log n+\xi(n))}{2\theta n}$, *and* $m(n) = n\log n$, $k(n) = n\log n$, *for fixed* $\gamma < 1$,

$$mk\prod_{y=1}^{u}(1-\frac{2\theta\phi_y r_y(n)}{3\pi^2})^{c_y n} \geq \gamma e^{-\xi}, \tag{20}$$

holds for all sufficient large n.

proof: Using the same approaching for Lemma 2

Now, we present the following proposition regarding the necessary condition.

Proposition 5 *In the mobile heterogeneous CSN with 1-dimensional random walk mobility model, if* $r_{1.r.w.} = \frac{3\pi(\log n+\log\log n+\xi(n))}{2\theta n}$ *and the density of the dense grid* $\mathbb{M}$ *is* $m = n\log n$*, the density of the orientation set* $\mathbb{K}$ *is* $k = n\log n$*, then*

$$\liminf_{n\to\infty} \mathbb{P}_\tau(\widehat{\mathcal{H}^\tau}) \geq \gamma e^{-\xi} - \frac{\theta}{\pi}e^{-4\xi},$$

where $\xi = \lim_{n\to\infty}\xi(n)$*.*

proof: Similar to the proof of Proposition 1, we first study the case where $r_{1.r.w.} = \frac{3\pi(\log n+\log\log n+\xi(n))}{2\theta n}$, for a fix ξ.

$$\begin{aligned}\mathbb{P}_\tau(\widehat{\mathcal{H}^\tau}) \geq & \sum_{P_i\in\mathbb{M}}\sum_{O_j\in\mathbb{K}} \mathbb{P}_\tau(\{O_j \text{ of } P_i \text{ is uncovered}\}) \\ & - \sum_{P_i\in\mathbb{M}}\sum_{O_j,O_h\in\mathbb{K}}^{O_j\neq O_h} \mathbb{P}_\tau(\{O_j \text{ and } O_h \text{ of } P_i \text{ are uncovered}).\end{aligned} \tag{21}$$

And we calculate that

$$\mathbb{P}_\tau(\{O_j\ of\ P_i\ is\ uncovered\}) = \prod_{y=1}^{u}(1-\frac{2\theta\phi_y r_y(n)}{3\pi^2})^{c_y n}.$$

Using Lemma 3, we bound the first term of R.H.S of Eq. (21),

$$\sum_{P_i\in\mathbb{M}}\sum_{O_j\in\mathbb{K}} \mathbb{P}_\tau(\{O_j\ of\ P_i\ is\ uncovered\}) \geq \gamma e^{-\xi}, \tag{22}$$

for any $\gamma > 1$ and all $n > N_\xi$.

Then we bound the second term

$$\begin{aligned}
&\sum_{P_i \in \mathbb{M}} \sum_{O_j, O_h \in \mathbb{K}}^{O_j \neq O_h} \mathbb{P}_\tau(\{O_j \text{ and } O_h \text{ of } P_i \text{ are uncovered}) \\
&\qquad \leq mk^2 \frac{2\theta}{2\pi} \prod_{y=1}^{u} (1 - \frac{r_y(n)\phi_y\theta}{\pi^2})^{c_y n} \\
&\qquad + mk^2 (1 - \frac{2\theta}{2\pi}) \prod_{y=1}^{u} (1 - \frac{4}{3}\frac{r_y(n)\phi_y\theta}{\pi^2})^{c_y n} \\
&\qquad \sim mk^2 \frac{\theta}{\pi} e^{-\frac{2n\theta}{\pi}\sum_{y=1}^{u} c_y \frac{\phi_y}{2\pi} r_y(n)} \\
&\qquad + mk^2 (1 - \frac{\theta}{\pi}) e^{-\frac{8n\theta}{3\pi}\sum_{y=1}^{u} c_y \frac{\phi_y}{2\pi} r_y(n)} \\
&\qquad = mk^2 \frac{\theta}{\pi} e^{-\frac{2n\theta}{\pi} r_{1.r.w.}} + mk^2 (1 - \frac{\theta}{\pi}) e^{-\frac{8n\theta}{3\pi} r_{1.r.w.}} \\
&\qquad = \frac{\theta}{\pi} e^{-3\omega} + (1 - \frac{\theta}{\pi}) e^{-4\omega} \frac{1}{n \log n}.
\end{aligned} \tag{23}$$

Since we consider the asymptotic coverage problem, which means that the total number of cameras n approaches to infinity. Then we have

$$\mathbb{P}_\tau(\widehat{\mathcal{H}^\tau}) \geq \gamma e^{-\xi} - \frac{\theta}{\pi} e^{-3\xi}. \tag{24}$$

Taking into account that ξ is a function of n, the conclusion still holds.

According to Proposition 5, we know that $R_{1.r.w.} \geq \frac{3\pi(\log n + \log\log n)}{2\theta n}$ is necessary to achieve the full view coverage of $\mathbb{M}$.

Moreover, if sensing range is less than $\sqrt{\frac{3}{2}}$ of ESR of the 1-dimensional random walk mobility model, we could extend our result to the following Theorem.

Theorem 8 *Under the uniform deployment with the 1-dimensional random walk mobility model, if the CSN satisfy*

$$r(n) < \sqrt{\frac{3}{2}} R_{1.r.w.},$$

then it is necessary for the network to achieve almost surely coverage.

proof: Using similar method as the proof of Theorem 3, we could easily prove Theorem 8.

6.2.3 Sufficient ESR for Full View Coverage of the Dense Grid

First, we obtain the following proposition.

Proposition 6 *In CSN, if n sensors are randomly and uniformly deployed in a unit square, and* $r_{1.r.w.} = cR_{1.r.w.}(n)$ *where* $c > 1$*, then*

$$\liminf_{n\to\infty} \mathbb{P}_\tau(\widehat{\mathcal{H}_\tau}) = 0. \tag{25}$$

proof: Using similar approach as Proposition 2, this proposition can be proven.

$$\begin{aligned}\mathbb{P}_\tau(\widehat{\mathcal{H}_\tau}) &= \mathbb{P}_\tau(\bigcup_{i=1}^{m}\mathcal{F}_i) \\ &\le mk\prod_{y=1}^{u}(1-\frac{2\theta\phi_y r_y(n)}{3\pi^2})^{c_y n} \\ &\sim (n\log n)^2 e^{-\frac{4\theta}{3\pi}nr_{1.r.w.}} \\ &= \frac{1}{(n\log n)^{2c^2-2}} \to 0,\end{aligned} \tag{26}$$

for any $c > 1$.

From Proposition 5 and the definition of critical ESR for 1-dimensional random walk mobility model, we know that $R_{1.r.w.} \ge \frac{3\pi(\log n+\log\log n)}{2\theta n}$ is sufficient to achieve the full view coverage of $\mathbb{M}$.

Moreover, if sensing range is more than $\sqrt{\frac{3}{2}}$ of ESR of the 1-dimensional random walk mobility model, we could extend our result to the following Theorem.

Theorem 9 *Under the uniform deployment with 1-dimensional random walk mobility model, if the CSN satisfy*

$$r(n) > \sqrt{\frac{3}{2}}R_{1.r.w.},$$

then it is sufficient for the network to achieve almost surely coverage.

proof: Using similar method as the proof of Theorem 4, we could easily prove Theorem 9.

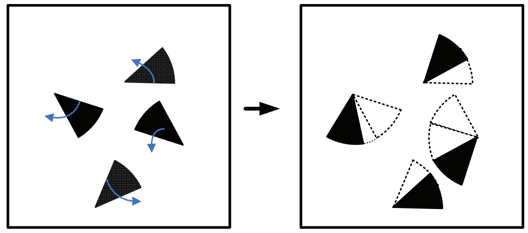

Figure 4: Full view coverage of CSNs under random rotating walk: the left figure depicts the initial network configuration at the beginning of one time slot, and the right figure illustrates the effect of sensor mobility in this time slot. The solid disks constitute the area being covered at the given time instant, and the union of the region inside the dotted line and the solid disks represents the area being covered in this slot.

6.2.4 Critical ESR for Full View Coverage of the Operational Range

Similar to the analysis in the static model, we can reach the following theorem.

Theorem 10 *Under the uniform deployment with 1-dimensional random walk mobility model, the critical ESR for mobile heterogeneous CSNs to achieve asymptotic full view coverage is* $R_{1.r.w.}(n) = \frac{3\pi(\log n + \log\log n)}{2\theta n}$.

6.3 Critical ESR Under Random Rotating Mobility Model

We investigate the situation in one time slot under the random rotating mobility pattern. Figure 4 illustrates the effect of random rotating mobility of the sensor on area coverage. We still first analyze the full view coverage for dense grid $\mathbb{M}$, and then expand it to the whole area.

6.3.1 Failure Probability of an Orientation in $\mathbb{K}$

Similarly, $\mathcal{F}_{i,j}$ denotes the event that orientation O_j of point P_i is not θ-viewed covered, and $\mathbb{P}(\mathcal{F}_{i,j})$ denotes the corresponding probability. $\mathbb{P}_{i,j,S_y}$ is the same as that under 2-dimensional random walk mobility model.

Then we can obtain

$$\begin{aligned}\mathbb{P}_{i,j,S_y} &= \mathbb{P}(\text{S falls in } T_j) \times \mathbb{P}(\text{S has proper orientation}) \\ &= \pi r_y^2(n) \times \frac{2\theta}{2\pi} \times \mathbb{P}(\text{S has proper orientation})\end{aligned} \tag{27}$$

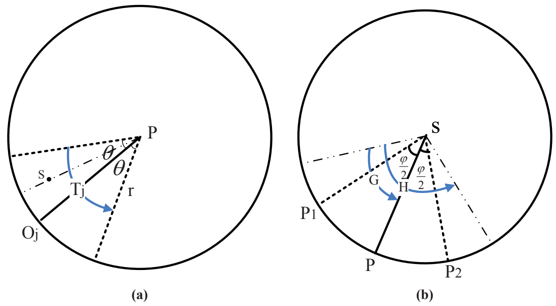

Figure 5: The figure on the left shows the sensor locates in T_j and the supposed viewed direction, a nd on the right illustrates the rotating process of the sensor.

The sensor has proper orientation means that the supposed viewed direction $\overrightarrow{PS}$ locates in the sensing region of the sensor. We will first calculate the probability that sensor S has proper orientation, which is denoted as $\mathbb{P}(S)$ in the following.

The initial angle from the bisector of the sensor to $\overrightarrow{PS}$ is denoted as G, a variable random uniformly distributed from 0 to 2π according to the deployment pattern. And the angle the sensor moves in a time slot is denoted as H, which is also a random variable distributed uniformly from 0 to 2π. Still, the sensor can rotate clockwise or counterclockwise, and the results are the same.

As shown in Figure 5, we set orientation $\overrightarrow{PS}$ as angle 0. When the bisector of the sensor initially locates in the sectorial area between $\overrightarrow{P_1S}$ and $\overrightarrow{P_2S}$, it can surely have a proper orientation. Otherwise when it moves counterclockwise, the bisector should go through $\overrightarrow{P_1S}$, and when clockwise, the bisector should come cross $\overrightarrow{P_2S}$, which can be formulated as

$$\begin{cases} G - H < \frac{\phi_y}{2} & \text{if S moves counterclockwise,} \\ G + H > 2\pi - \frac{\phi_y}{2} & \text{if S moves clockwise.} \end{cases} \tag{28}$$

When the sensor moves clockwise, we obtain

$$\begin{aligned} \mathbb{P}(S) &= \frac{\phi_y}{2\pi} + (1 - \frac{\phi_y}{2\pi})\mathbb{P}(G + H > 2\pi - \frac{\phi_y}{2}) \\ &= \frac{\phi_y}{2\pi} + (1 - \frac{\phi_y}{2})(\frac{1}{2} + \frac{\phi_y}{4\pi}) \\ &= \frac{1}{2}\left(1 + \frac{\phi_y}{\pi} - \frac{\phi_y^2}{4\pi^2}\right). \end{aligned} \tag{29}$$

When the sensor moves counterclockwise, similarly,

$$\mathbb{P}(S) = \frac{1}{2}\left(1 + \frac{\phi_y}{\pi} - \frac{\phi_y^2}{4\pi^2}\right).$$

Then we have

$$\mathbb{P}_{i,j,S_y} = \pi r_y(n)^2 \times \frac{2\theta}{2\pi} \times \mathbb{P}(S) \\ = \frac{\theta r_y^2(n)}{2}(1+\frac{\phi_y}{\pi} - \frac{\phi_y^2}{4\pi^2}). \tag{30}$$

Then, $\mathbb{P}(\mathcal{F}_{i,j})$ can be easily calculated.

6.3.2 Necessary ESR for Full View Coverage of the Dense Grid

Here, we use $\widehat{\mathcal{H}^\tau}$ denote the event that the dense grid $\mathbb{M}$ is not fully full view covered in the time slot τ. We have the following lemma.

Lemma 4 *If* $r_{r.r.} = \sqrt{\frac{4(\log n+\log(\log n)+\xi(n))}{n\theta}}$, *and* $m(n) = n\log n$, $k(n) = n\log n$, *for fixed* $\gamma < 1$,

$$mk\prod_{y=1}^{u}\left[1-\frac{\theta}{2}(1+\frac{\phi}{\pi}-\frac{\phi^2}{4\pi^2})r_y^2(n)\right]^{c_y n} \geq \gamma e^{-\xi}, \tag{31}$$

holds for all sufficient large n.

proof: Using the same approaching for Lemma 2.

Now, we present the following proposition regarding the necessary condition.

Proposition 7 *In the mobile heterogeneous CSN with random rotating mobility model, if* $r_{r.r.} = \sqrt{\frac{4(\log n+\log(\log n)+\xi(n))}{n\theta}}$ *and the density of the dense grid* $\mathbb{M}$ *is* $m = n\log n$, *the density of the orientation set* $\mathbb{K}$ *is* $k = n\log n$, *then*

$$\liminf_{n\to\infty} \mathbb{P}_\tau(\widehat{\mathcal{H}^\tau}) \geq e^{-\xi} - e^{-4\xi},$$

where $\xi = \lim_{n\to\infty}\xi(n)$.

proof: We use similar approaching as Proposition 1. Firstly, we study the case where $r_{r.r.} = \sqrt{\frac{4(\log n+\log(\log n)+\xi)}{n\theta}}$, for a fix ξ.

$$\mathbb{P}_\tau(\widehat{\mathcal{H}^\tau}) \geq \sum_{P_i\in\mathbb{M}}\sum_{O_j\in\mathbb{K}}\mathbb{P}_\tau(\{O_j \text{ of } P_i \text{ is uncovered}\}) \\ - \sum_{P_i\in\mathbb{M}}\sum_{\substack{O_j\neq O_h \\ O_j,O_h\in\mathbb{K}}}\mathbb{P}_\tau(\{O_j \text{ and } O_h \text{ of } P_i \text{ are uncovered}). \tag{32}$$

And we calculate that

$$\mathbb{P}_\tau(\{O_j\ of\ P_i\ is\ uncovered\})$$
$$=\prod_{y=1}^{u}(1-\frac{\theta}{2}(1+\frac{\phi}{\pi}-\frac{\phi^2}{4\pi^2})r_y^2(n))^{c_y n}.$$

Using Lemma 4, we bound the first term of R.H.S of Eq. (32),

$$\sum_{P_i\in\mathbb{M}}\sum_{O_j\in\mathbb{K}}\mathbb{P}_\tau(\{O_j\ of\ P_i\ is\ uncovered\})\geq e^{-\xi}, \tag{33}$$

for any $\gamma > 1$ and all $n > N_\xi$.

Similarly, we could bound the second term of R.H.S of Eq. (32),

$$\sum_{P_i\in\mathbb{M}}\sum_{O_j,O_h\in\mathbb{K}}^{O_j\neq O_h}\mathbb{P}_\tau(\{O_j \text{ and } O_h \text{ of } P_i \text{ are uncovered})\sim e^{-4\xi}. \tag{34}$$

Since we consider the asymptotic coverage problem, which means that the total number of cameras n approaches to infinity. Then we have

$$\mathbb{P}_\tau(\widehat{\mathcal{H}^\tau})\geq\gamma e^{-\xi}-e^{-4\xi}.e^{-3\xi}. \tag{35}$$

Taking into account that ξ is a function of n, the conclusion still holds.

According to Proposition 7, we know that $R_{r.r.}=\sqrt{\frac{4(\log n+\log(\log n))}{n\theta}}$is necessary to achieve the full view coverage of $\mathbb{M}$.

Furthermore, the result holds for when ξ changes, thus we finish the necessary part.

Moreover, if sensing range is less than $\sqrt{\frac{3}{2}}$ of ESR of the random rotating mobility model, we could extend our result to the following Theorem.

Theorem 11 *Under the uniform deployment with the random rotating mobility model, if the CSN satisfy*

$$r(n)<\sqrt{\frac{3}{2}}R_{r.r.},$$

then it is necessary for the network to achieve almost surely coverage.

proof: Using similar method as the proof of Theorem 3, we could easily prove Theorem 11.

6.3.3 Sufficient ESR for Full View Coverage of the Dense Grid:

Similarly, we obtain the following proposition.

Proposition 8 *In CSN, if n sensors are randomly and uniformly deployed in a unit square, and* $r_{r.r.} = cR_{r.r.}(n)$ *where* $c > 1$, *then*

$$\liminf_{n\to\infty} \mathbb{P}_\tau(\widehat{\mathcal{H}_\tau}) = 0. \tag{36}$$

proof: Using same technique as Proposition 2, we could prove the proposition.

$$\begin{aligned}\mathbb{P}_\tau(\widehat{\mathcal{H}_\tau}) &= \mathbb{P}_\tau(\bigcup_{i=1}^{m}\mathcal{F}_i)\\ &\le mk\prod_{y=1}^{u}(1-\frac{\theta}{2}(1+\frac{\phi}{\pi}-\frac{\phi^2}{4\pi^2})r_y^2(n)\Big]^{c_y n}\\ &\sim (n\log n)^2 e^{-\frac{n\theta}{2}r_{r.r.}^2}\\ &= \frac{1}{(n\log n)^{2c^2-2}} \to 0,\end{aligned} \tag{37}$$

for any $c > 1$.

From Proposition 8 and the definition of critical ESR for random rotating mobility model, we know that $R_{r.r.} \ge \sqrt{\frac{4(\log n+\log(\log n))}{n\theta}}$ is sufficient to achieve the full view coverage of $\mathbb{M}$.

Moreover, if sensing range is more than $\sqrt{\frac{3}{2}}$ of ESR of the random rotating mobility model. model, we could extend our result to the following Theorem.

Theorem 12 *Under the uniform deployment with random rotating mobility model, if the CSN satisfy*

$$r(n) > \sqrt{\frac{3}{2}}R_{r.r.},$$

then it is sufficient for the network to achieve almost surely coverage.

proof: Using similar method as the proof of Theorem 4, we could easily prove Theorem 12.

Table 1: Comparison of ESR and CSR

Network Type	ESR for heterogeneous network	CSR for homogeneous netwo
Static Model	$R(n) = \sqrt{\frac{2(\log n+\log\log n)}{n\theta}}$	$R(n) = \sqrt{\frac{4\pi(\log n+\log\log n)}{n\theta\phi}}$
2-dimensional Random Walk Mobility	$R(n) = \begin{cases} \frac{\log n+\log\log n}{2nTv\sin\theta} & \text{if } \theta < \frac{\pi}{2} \\ \frac{\log n+\log\log n}{2nTv} & \text{if } \theta \geq \frac{\pi}{2} \end{cases}$	$R(n) = \begin{cases} \frac{\pi(\log n+\log\log n)}{nTv\phi\sin\theta} & \text{if} \\ \frac{\pi(\log n+\log\log n)}{nTv\phi} & \text{if} \end{cases}$
1-dimensional Random Walk Mobility	$R(n) = \frac{3\pi(\log n+\log\log n)}{2\theta n}$	$R(n) = \frac{3\pi^2(\log n+\log\log n)}{\theta n\phi}$
Random Rotating Mobility	$R(n) = \sqrt{\frac{4(\log n+\log(\log n))}{n\theta}}$	$R(n) = \sqrt{\frac{4(\log n+\log(\log n))}{n\theta(1+\frac{\phi}{\pi}-\frac{\phi^2}{4\pi^2})}}$

6.3.4 Critical ESR for Full View Coverage of the Operational Range

Similar to the analysis in the static model, we can reach the following theorem.

Theorem 13 *Under the uniform deployment with random rotating mobility model, the critical ESR for mobile heterogeneous CSNs to achieve asymptotic full view coverage is* $R_{r.r.}(n) = \sqrt{\frac{4(\log n+\log(\log n))}{n\theta}}$.

7 Critical Condition for Homogeneous Camera Sensor Networks

In the above discussions, we mainly focus on the heterogeneous static and mobile networks, which means sensors may have different sensing parameters like sensing radius and sensing angle. Here we could easily expand our result to homogeneous case, where sensors all have identical sensing parameters. The process is quite similar, we only provide the main results here.

- With static model, the critical sensing radius (CSR) is $R(n) = \sqrt{\frac{4\pi(\log n+\log\log n)}{n\theta\phi}}$.
- With 2-dimensional random walk mobility model, the CSR is

$$R(n) = \begin{cases} \frac{\pi(\log n+\log\log n)}{nTv\phi\sin\theta} & \text{if } \theta < \frac{\pi}{2} \\ \frac{\pi(\log n+\log\log n)}{nTv\phi} & \text{if } \theta \geq \frac{\pi}{2} \end{cases}$$

- With 1-dimensional random walk mobility model, the CSR is $R(n) = \frac{3\pi^2(\log n+\log\log n)}{\theta n\phi}$.

- With random rotating mobility model, the CSR is $R(n) = \sqrt{\frac{4(\log n + \log(\log n))}{n\theta(1+\frac{\phi}{\pi}-\frac{\phi^2}{4\pi^2})}}$.

In Corollary 5.1 of [2], Kumar presented that in a static and homogeneous network under uniform deployment,

$$c(n) \geq 1 + \frac{\phi(np) + k \log\log(np)}{\log(np)},$$

is sufficient for a unit square to be asymptotically k-covered, where $c(n) = \frac{np\pi r^2}{\log(np)}$, $\phi(np) = o(\log\log(np))$ and p is the probability that a sensor is currently operating. By assuming $p = 1$, $k = 1$, and ignoring $\phi(np)$ as $n \to \infty$, we translate this landmark result to our model. We obtain

$$r \geq \sqrt{\frac{(\log n + \log\log n)}{n\theta}},$$

which matches our result under static model, taking $\phi = 2\pi$ to represent omni-directional sensors. This result verify the generality of our model.

We present the result in homogeneous network and heterogeneous network together in Table 1.

8 Simulation and Performance Evaluation

8.1 Simulation and Numerical Results

In this part, we do simulation to validate the theoretical results on critical ESR to achieve full view coverage. Moreover, we can study the relationship between ESR and the percentage of full view coverage.

8.1.1 Simulation Setup

We take the static model as an example. The simulation can be easily extended to the other three mobile models. The target area is a unit square. We use two settings for sensor density: $n = 25 * 25$ and $n = 100 * 100$. For simplicity, we consider the homogeneous case, namely all the sensors have the same sensing parameter (sensing radius and angle). The effective angle is fixed, and we use three values for the fixed effective angle, i.e., $\theta = \pi/6, \pi/4, \pi/3$ (or 30, 45, 60 in degree) respectively.

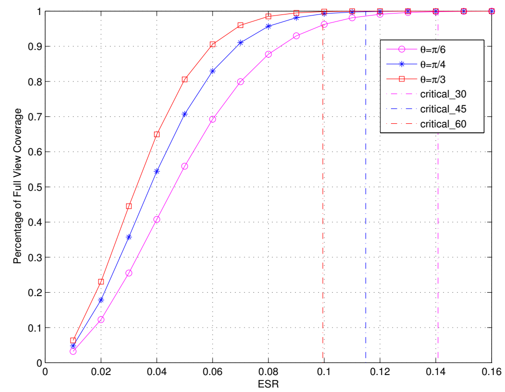

Figure 6: Relationship between equivalent sensing range $R(n)$ and percentage of full view coverage, when sensor density $n = 625$

We vary the ESR from 0 to 0.16 for $n = 625$, and from 0 to 0.05 for $n = 10000$, to observe the percentage of full view coverage. The percentage of full-view coverage is defined to be the percentage of points that are full view covered.

8.1.2 Simulation Result Analysis

Figure 6 and 7 show the result of the percentage of full view coverage under different ESR. We use x-axis to denote the percentage of full view coverage and y-axis to denote the ESR. The results shown here are for $n = 625$ and $n = 10000$. In both cases, the ESR needed for full view coverage increases as the required probability increases, although the ESR for $n = 10000$ is much lower than the ESR for $n = 625$. According to the formulation derive in Section 5, we calculate the critical ESR for full view coverage when $\theta = \pi/6, \pi/4, \pi/3$ (or 30, 45, 60 in degree) respectively, and use dotted lines to indicate the critical ESR on Figure 6 and 7. It is clear that the network is able to achieve full view coverage with probability one when ESR is larger than the critical ESR, which verified our result of critical condition.

Moreover, from Figure 6 and 7, we can see that although the ESR needed to achieve full view coverage for the whole area may be high, the ESR needed for a high percentage (but not 100%) of full view coverage is much lower. For example, given $\theta = \pi/3$ and sensor density $n = 10000$, 90% of the field is full view covered when ESR $r(n) = 0.015$, which is only around half of the required critical ESR to achieve 100% full view coverage with ESR $r(n) = 0.0296$. So our results can

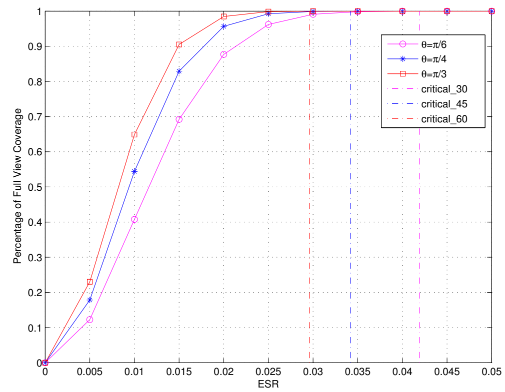

Figure 7: Relationship between equivalent sensing range $R(n)$ and percentage of full view coverage, when sensor density $n = 10000$

help the engineers to design the CSN according to certain engineering requirements by balancing coverage performance and ESR.

8.2 Impact of Mobility on Sensing Energy Consumption

We consider the impact of mobility here. Sensors are considered to have critical ESR, with radius $r_y = r_i, i = stat, 2.r.w., 1.r.w., r.r.$, under static, 2-dimensional random walk, 1-dimensional random walk, and random rotating correspondingly. As we just convert the value of the angle of each sensor to the weight of its radius when we derive the critical ESR, the sensors can be viewed as omnidirectional traditional sensors and we here use the area the sensor covers to represent the sensing energy consumption of it.

We have the following results

(a) Under Static Model:

$$\overline{E}_{stat} = \Theta(\frac{\log n + \log\log n}{n}). \tag{38}$$

(b) Under 2-Dimensional Random Walk Mobility Model:

$$\overline{E}_{2.r.w.} = \Theta((\frac{\log n + \log\log n}{n})^2). \tag{39}$$

(c) Under 1-Dimensional Random Walk Mobility Model:

$$\overline{E}_{1.r.w.} = \Theta((\frac{\log n + \log\log n}{n})^2). \tag{40}$$

(d) Under Random Rotating Mobility Model:

$$\overline{E}_{r.r.} = \Theta(\frac{\log n + \log\log n}{n}). \tag{41}$$

Therefore, taking static model as a baseline, we have

$$\overline{E}_{2.r.w.} = \overline{E}_{1.r.w.} = \Theta(\frac{\log n + \log\log n}{n}) \times \overline{E}_{stat},$$

$$\overline{E}_{r.r.} = \overline{E}_{stat},$$

which indicates that compared with static model, both the 2-dimensional random walk mobility model and 1-dimensional random walk mobility model can decrease the energy consumption in CSNs. And this improvement sacrifices the delay upper bounded by $\Theta(1)$ as the movement is divided into time slots. This is actually a tradeoff between energy consumption and the delay.

However, for random rotating mobility, the energy consumption is the same as when sensors are stationary, but it still causes a delay upper bounded by $\Theta(1)$, due to the division of the time slots. Furthermore, this results in much more energy consumption for movement. Thus, the movements like random rotating should be avoided for full view coverage.

More importantly, from previous theoretical analysis we could conclude that when we consider the critical sensing range under 2-dimensional random walk mobility model and 1-dimensional random walk mobility model, the rectangular area the sensor covers when it moves contributes most for coverage performance rather than the sectorial area it covers when it is static. For instant, under 2-dimensional random walk mobility model, the area $\theta r_y^2(n)$ in Eq. (12) does not make any difference for the final result.

8.3 Impact of Parameter n and θ

Here we analyze the influence of n and θ on the critical equivalent sensing range denoted by $R(n)$. Figure 8 illustrates the relationship between critical equivalent sensing range $R(n)$ and θ, when n changes accordingly under 1-dimensional random walk mobility model. Figure 9 illustrates the relationship between critical equivalent sensing range $R(n)$ and n, when θ changes accordingly under 1-dimensional random walk mobility model.

When n is fixed, $R(n)$ becomes larger, as θ decreases for all the static and mobility patterns we have discussed. So we need sensors of larger sensing range when a better view of object's

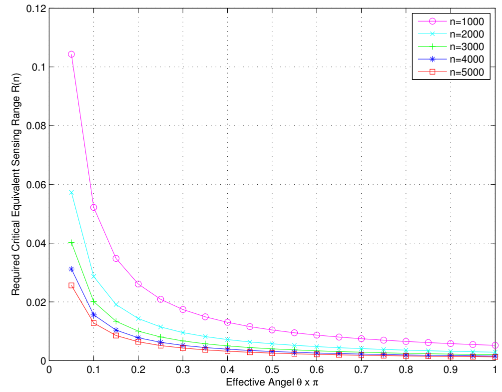

Figure 8: Relationship between critical equivalent sensing range $R(n)$ and θ, when n changes accordingly under 1-dimensional random walk mobility model

face is required. It is obvious since larger sensing region render more sensors to cover a certain object, thus having more chance to catch its frontal image. When it is large enough (like n=4000, 5000 in Figure 8 as an example), n will not further influence the network performance. This fact corresponds with the instinct that when there are plenty of sensors in the network, adding more sensors will not further reduce the critical equivalent sensing range. Furthermore, as shown in Figure 8, changing n will lead to greater change of $R(n)$ for smaller effective angle θ, but n will has little influence on $R(n)$ when θ goes to π. We can analyze Figure 9 similarly.

9 Conclusion

Coverage property of camera sensor networks is a fundamental issue, among which full view coverage draws lots of attention due to its emphasis on capturing the objects' face. In this paper, we study the static and mobile models for Camera Sensor Networks. We mainly focus on heterogeneous camera network and define a parameter named Equivalent Sensing Range (ESR) to model it. Furthermore, we derive the critical sensing range for full view coverage under static model, 2-dimensional random walk mobility model, 1-dimensional random walk mobility model and random rotating model. The results indicate that random walk mobility model can decrease the sensing energy consumption under certain delay tolerance. These formulations not only provide an asymptotic description of the critical power needed to maintain the full view

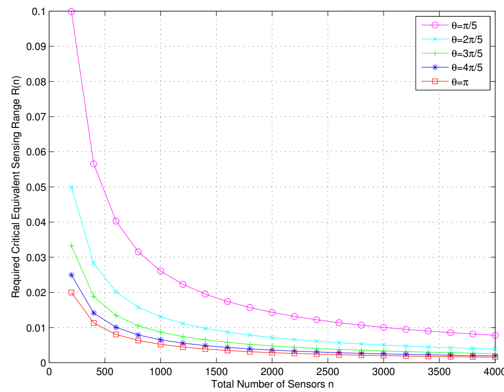

Figure 9: Relationship between critical equivalent sensing range $R(n)$ and n, when θ changes accordingly under 1-dimensional random walk mobility model

coverage, but also help to identify the impact of mobility on the network. Our results offer some valuable insights for the analysis and design of camera sensor networks, especially for high quality service.

Furthermore, we find that the network is sufficient to achieve almost surely coverage when ESR is large enough ($c > 1.225$), which is a much stronger result compared with the traditional network who can only ensure coverage with probability one. We also extend our result from heterogeneous networks to homogeneous networks, and derive both ESR and CSR for heterogeneous networks and homogeneous network respectively.

There are some interesting topics for future work. Firstly, we would like to investigate the situation when sensors could cooperate with each other, exchanging their orientation and location information. Moreover, we would like to consider that there are obstacles in CSNs. Last but not the least, it is interesting to study the conditions for CSNs to achieve k-full view coverage.

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