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tk-coverage: Time-based *K*-Coverage for energy efficient monitoring

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Abstract

K-coverage is a classic issue in wireless sensor network (WSN) deployment. Existing works typically assumes that every position in the monitoring field is covered by at least k sensor nodes at any given time. This may not always be necessary because certain events to be monitored will last only for a short period of time. Based upon such observation, we include the time dimension in the original *k*-coverage problem, and denote it as *tk*-coverage In the context of *tk*-coverage, sensor nodes can apply periodical sleeping strategies to save energy use. A corresponding *tk*-coverage (TKC) model is proposed to analyze the energy consumption and detection delay., The proposed *tk*-coverage can balance energy consumption and detection delay by adjusting the sleeping strategies of sensor nodes. Comprehensive simulations have been conducted to validate the effectiveness and demonstrate the efficiency of this solution.

1. Introduction

Many efforts have been made to address the *k*-coverage problem in Wireless Sensor Networks (WSNs). To the best of our knowledge, all previous works make the same natural assumption: every position must be *k*-covered at any time during the entire monitoring process. That is to say, the *k*-coverage problem suggests a real-time event monitoring scheme. However, this requirement is often not necessary because the events to be detected may last only for a short period of the time.. For those short-lived events, it is sufficient to monitor them only during their occurrence.

To explain this concept, let's turn to an ordinary example. Imagine a long bridge connects two countries, A and B. A soldier of country A is patrolling to monitor the stowaway coming from country B, the other side of the bridge. The problem now becomes, "does the soldier need to patrol all the time?" Obviously, the answer is NO. Suppose p minutes is the shortest time possible for people to get through the bridge. The solder only need to monitor in every q minutes if $q < p$. This is enough to ensure the discovery of any stowaway and save a good deal of human energy.

In previous example, patrolling at intervals can save the energy of an individual soldier without missing monitoring the border line. If a WSN is employed to do the same task, how do we deploy thousands of those energy-limited sensors? This problem is significant for WSN applications. In this study, we propose *tk*-coverage strategy, which introduces a new factor, time, into the traditional *k*-coverage problem.

Essentially, the introduction of the time dimension releases the real-time constraint from the traditional *k*-coverage problem. And by its nature, time-insensitive WSN applications do not need real-time *k*-coverage. The new Time-based *k*-coverage (*tk*-coverage) will bring delay for event detection because it only guarantees the detection during a small window of time. But *tk*-coverage can save a great deal of energy due to the periodic sleeping and awaking scheme. Therefore, *tk*-coverage will have much better energy efficiency, which is often viewed as one of the most critical issues for WSN in practice. In

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summary, *tk*-coverage is significant, especially in the following two kinds of scenarios:

1. The targeted events will last only for a short period of time.

   For example, in the traffic system, sensors are used to detect the inter-meeting events of two buses. The sensors deployed on the buses can detect each other and communicate with each other when they come into the detection range (tens of meters). Such communication process usually lasts for a very short period. Therefore, the sensor only needs to work periodically without missing any events.

2. Some applications can tolerate short detection delays.

   For example, in a farm insect monitoring system, situations we are interested in will not change rapidly, it is acceptable to monitoring at intervals.

The contributions of this study are as follows. Taking both time and coverage into consideration, we first formulate the *tk*-coverage problem. We then present the *tk*-coverage model (TKC) that combines the coverage and sleeping strategy to save energy use. Theoretical analysis is given to show that the proposed approach can strike a good balance between energy efficiency and detection latency by adjusting the sleeping strategy of sensor nodes. The influences of some key parameters for TKC are discussed to help understand the performance of TKC. Comprehensive simulations are conducted to validate the effectiveness of the proposed solutions and study its performance.

The rest of this paper is organized as follows. Section 2 introduces the background and related work. Section 3 formulates the *tk*-coverage problem and proposes the corresponding TKC model. The theoretical analysis of the TKC model is presented in Section 4. Extensive simulations are conducted to validate the proposed model and solution in Section 5. Finally, we conclude our work and the directions of future work in Section 6.

2. Background and Related Work

Recent advances in WSNs attract the attention of a lot of researchers [8-10, 13, 15, 18] with many efforts have been made in coverage problem. The coverage problem is of great importance for applications such as battlefield surveillance, environment monitoring and biological detection [1, 3, 11]. Researchers have great interests in all aspects of coverage problem, including the sensor node deployment [22], energy efficiency coverage [16], point coverage [2] and barrier coverage [7], etc.

K-coverage [16] is an important extension of the classical full coverage problem. Circle coverage has been used to solve the problem by mathematic analysis [4, 12, 14]. However, earlier approaches ignore the energy consumption, a critical problem of wireless sensor networks. Slijepcevie etc. [16] first discussed how to extend the lifetime of network by periodically alternant sleeping and awaking. Based on this principle, a number of distributed schedule algorithms were proposed to find the optimal solution by Ye etc. [21], Tian etc [17], Yan etc. [20]. And other related work had been conducted under various constrains, by Hsin etc. [5], Huang etc. [6], Xing etc. [19].

However, to the best of our knowledge, all existing works aim to achieve *k*-coverage at any given time. The proposed *tk*-coverage, on the other hand, is a novel concept in that it is the first approach that releases the real-time detection constraint. This set *tk*-coverage apart from previous works.

3. Problem Formulation

Suppose an area A is covered by N sensor nodes, denoted by i ($i = 1,\ldots,N$), each of which has an individual cover function $f(i, x)$ (x is a position in A). The function $f(i, x)$ is 1 if and only if $n(i)$ covers x:

$$f(i,x)=\begin{cases}1, & x \text{ is coverd by } i^{\text{th}} \text{ node}\\ 0, & \text{otherwise}\end{cases}$$

Hence, the classical k-coverage at x indicates:

$$\sum_{i=1}^{N} f(i,x) \geq k$$

The concept of tk-coverage is similar to the classical k-coverage. But the new cover function, $f(i, x, t)$, includes the time dimension as the third variable. The new definition is as follows:

$$f(i,x,t)=\begin{cases}1, & x \text{ is coverd by } i^{\text{th}} \text{ node at time } t\\ 0, & \text{otherwise}\end{cases}$$

Intuitively, the tk-coverage can be simplified as 'have been k-covered during a period of time'. Hence, we focus on a set of nodes L that covers position x during time $[0, u]$, denoted by:

$$L=\left\{ i \mid \int_0^u f(i,x,t)dt > 0, i=1,2,...,n \right\}$$

A position x is tk-covered if and only if $|L| \geqslant k$.

In addition, it is necessary to point out that all nodes discussed here are static: once they are deployed, their positions will not change in the future. Therefore, for an original deployment, the only effect factor of the network performance is the function $f(i, x, t)$ only. It implies that we can considering to improve the performance by scheduling all $f(i, x, t)$ in a distributed approach, which will be discussed in the next section.

4. The TKC Model

In this section, we define the TKC model that aims to solve the following problems:

1. What are the relationships among following variables:
    a) The interested time u: a variable that is typically determined by the applications.
    b) Coverage degree k: User specified coverage requirement.
    c) Number of nodes covering one position n.
    d) Working cycle time $T = a+b$, where a is the length of active time while b is the sleeping time.
    e) Active rate p_a: active time a divided by working cycle T to evaluate the energy cost.
    f)
2. How do we adjust variables described above to achieve k-coverage in u time?
3. As stated previously, tk-coverage will reduce the energy cost but incurs more delays. How do those two performance indices influence each other?
4. What is the impact of T, the length of working cycle time?

4.1 Parameters of the TKC model

We start our discussion from the first question. Suppose position x is covered by n nodes, each of which has a common working cycle T. Suppose each sensor works for a time of a, then sleep for a time of b. As mentioned before, active rate is defined as $p_a = a/T$, and it is considered a parameter to reflect the energy utilization. All nodes are independent to each other. Although all sensors have the same time cycle T, each of them has its own time shift that is usually different from others.

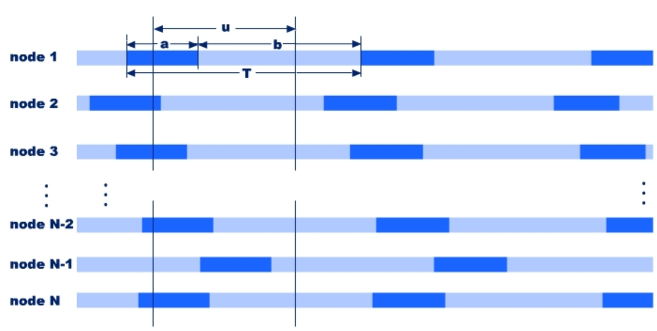


Figure 4.1.1: The explanation of relationships among tk-coverage variables

As illustrated in figure 4.1.1, N lines denote the states of N sensor nodes. In each line, the active period is denoted by the deep color in the time axis, while the sleeping period is denoted by the light color. Let u denote the time span of interested events, illustrated by the time intervals between two vertical lines in the figure.

Now we are able to explore the relationships among p_a and u, k, n. For sensor i, the cover function will be:

$$f(i,x,t)=\begin{cases}1, & t\in[nT,nT+a)\\ 0, & t\in[nT+a,(n+1)T)\end{cases}$$

Suppose s is the starting time of an event, which occurs somewhere at a cycle $[nT, (n+1)T)$. If $u >= b$, then active time a will intersect u regardless when s is. If on the other hand $u < b$, we define a coverage function $C(s)$ as follows:

$$C(s)=\begin{cases}1, & \text{if} \int_{s}^{s+u} f(i,x,t)dt>0\\ 0, & \text{if} \int_{s}^{s+u} f(i,x,t)dt=0\end{cases}$$

In any working cycle $[nT, (n+1)T)$, to ensure $C(s) = 1$, s should satisfy $nT\leqslant s\leqslant nT+a$ or $(n+1)T-u\leqslant s\leqslant(n+1)T$. Therefore, in every working cycle T, the probability of detecting the event by a single sensor is

$$P_1=\begin{cases}1 & u\geq b\\ \dfrac{a+u}{a+b} & u<b\end{cases} \tag{4.1.1}$$

Therefore, the probability of the event detected by N independent nodes is:

$$P_N=\sum_{i=k}^{N} C_N^i P_1^i (1-P_1)^{N-i} \tag{4.1.2}$$

4.2 The *tk*-coverage for duration *u*

From expression (4.1.1), to ensure that a position is covered by a node, we only need to deploy the network by setting b no smaller than u. Because all n nodes are independent to each other, k-coverage in duration u can be achieved with this setting.

This conclusion is interesting. Suppose active rate p_a is very small, TKC becomes a periodic awaking system. In other words, the periodic awaking system is a special case of TKC with a very small value of p_a. As we know, the periodic awaking system can save as much proportion of energy as possible but incur severe time delays for detecting. On the other extreme when $p_a = 1$, TKC becomes a real-time k-coverage network. It has no detection delay but suffers the highest energy consumption.

4.3 Tradeoff between the energy utilization and the time delay

First of all, we need to define the energy utilization and the time delay.

Considering a network for the traditional k-coverage, the total energy cost is denoted by a constant value Q. Therefore, the *tk*-coverage network with active rate p_a has the energy cost of:

$$Q' = Q\cdot p_a$$

Now let's calculate the extra delay caused by the loosed real-time constraint.

When an event occurs, each one of k nodes has p_a chance to be active and $(1 - p_a)$ to be sleeping. If node i is in the active state, the time delay is 0. Otherwise, the time delay d_i, defined by $\min\{\Delta t \mid f(i,x,t+\Delta t) = 1\}$, is a uniformly distributed random value in $[0, b]$.

Since all n nodes are independent, the delay of the network will be $d_a = 0$ if and only if at least one node is active, which has a probability of p_a^n. If all n nodes are sleeping, then the network delay d_b will be the minimum of all the n random values. Therefore, the expected delay is

$$E(D)=d_a\cdot[1-(1-p_a)^n]+d_b\cdot(1-p_a)^n$$

where $d_a = 0$,and $d_b=\min\{d_i\}$ $i = 1,2,\ldots,n$.

The expected value of d_b is

$$E(d_b) = \int_0^b xn\frac{1}{b}\left(\frac{b-x}{b}\right)^{n-1} dx$$

$$= n\frac{1}{b^n}\int_0^b x(b-x)^{n-1} dx$$

$$= \frac{b}{n+1}$$

Therefore, we have

$$E(D) = (1-p_a)^n \cdot E(d_b) = \frac{b}{n+1}(1-p_a)^n \qquad (4.3.1)$$

For a deployment with determined b and n, we can obtain different $E(D)$ by adjusting the parameter p_a. From expression (4.3.1), $E(D)$ decreases when p_a increases. If $p_a = 0$, the expected delay is $b/(n+1)$. If $p_a = 1$, the delay will be 0. And for any assignment of p_a between [0, 1], $E(D)$ will have a unique corresponding value in $[0,b/(n+1)]$.

We present the relationship between time delay and energy utilization in Figure 4.3.1. Each one of the four curves represents the relationship of energy utilization and the delay for a given coverage degree n.

As discussed above, the energy utilization follows a linear distribution while the delay is an exponential distribution. And extra delay differs with different n. For a particular application requirement, users can select the optimal p_a and achieve a good balance between the two.

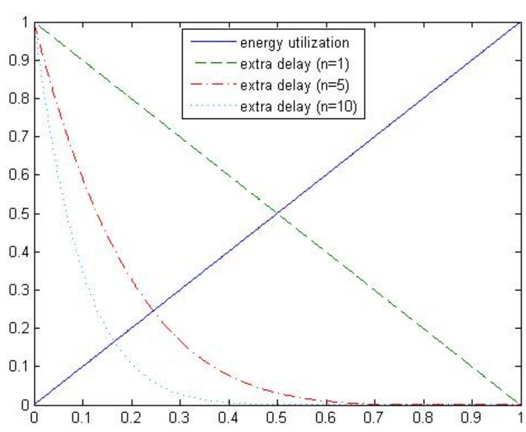


Figure 4.3.1: Tradeoff between the energy utilization and the extra delay

4.4 Influence of *n* and *T*

As mentioned before, the coverage probability has nothing to do with k. However, for a fixed p_a, n has a great impact on the expected delay $E(D)$.

$E(D)$ exponentially decreases along with n. For example, if $p_a = 0.1$, when $n = 1$, $E(D) = 0.45$,when $n = 5$, $E(D) = 0.0984$. That means, 5 nodes covered deployment can reduce the extra delay to 21.87% of the delay of one node covered deployment. This result shows a great advantage of *tk*-coverage, since the traditional *k*-coverage with a large value of p_a is not acceptable due to the energy consumption. Simulation results in next section also reinforced this conclusion.

Now examine working cycle T According to function (4.3.1), $E(D)$ is linear to b; that is to say, the smaller the b ,the shorter the extra delay. In a practical network, switching between the state of active and sleeping also contributes largely to the energy consumption. Therefore, the cost is linear to the switching frequency, the inverse to T. We can then evaluate the cost of both monitoring and switching. For example, we define the overhead O as:

$$O = c \cdot f = \frac{c}{T} = \frac{c\cdot(1-p_a)}{b}$$

where c is the constant overhead of switching and $f = 1/T$ is the switching frequency.

5. Numerical results and simulations

In this section, large-scale simulations are conducted to test the system scalability under different network settings. In our simulation, we varied two parameters, the active proposition p_a and the pre-defined n.

5.1 The simulation of extra delay with variable p_a

First, we present the simulation to validate the convergence of $E(D)$ defined in (4.3.1). Our approach is to generate a series of random uniformly distributed values and record the minimum. This process is repeated for many times. If $E(D)$ is convergent as expected, the more random values we run, the closer it is to the expected value.

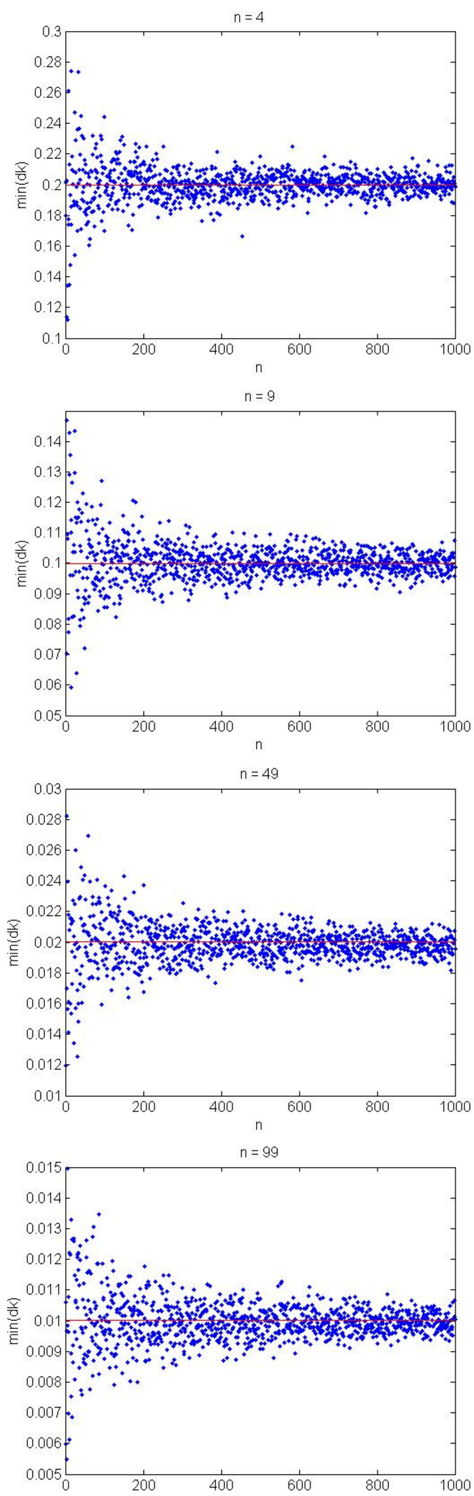


Figure 5.1.1: The convergence of *E(D)*

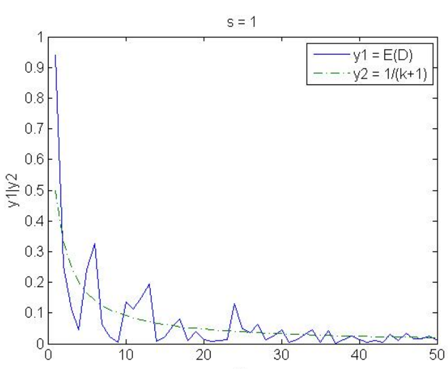
Figure 5.1.1 shows the simulation results. We generate n random value in [0, 1], where n is set to 4, 9, 49, 99, respectively. According to expression (4.3.1), $E(D)$ is expected to be 0.2, 0.1, 0.02, 0.001. Then we repeat the above process for i (i = 1, …, 1000) times to obtain i minimum values. We also calculate the average value of all this 1000 values, illustrated by a red line.

The x-axis is the repeating counter i; while the y-axis is the average minimum value from randomly generated values. It is clear that as the n increases, the average minimum value gets more and more closer to the expected value $1/(n+1)$, which is marked as a red line.

Also, we present a simulation to verify $E(D)$. Our approach is to obtain the average minimum values for different n in previous algorithm, then compare it to the expected value function curve. We then vary the repeating times to illustrate the convergent.

Consider k from 1 to 50, and for each n, we obtain the average minimum value for s (s = 1, 10, 100, 1000) times. And the curve is then compared to the situation when $y = 1/(1+x)$.

As show in Figure 5.1.2, the x-axis is n and y-axis is for both $y_1 = E(D)$ and $y_2 = 1/(x+1)$. As s increases, the curve of $E(D)$ approaches to $y2 = 1/(n+1)$. When $s = 1000$, two function curves already superpose and as mentioned before, for a WSN with numerous sensor nodes, $s = 1000$ is a very conservative assumption. Therefore the expression (4.3.1) is correct and practical for real deployment.



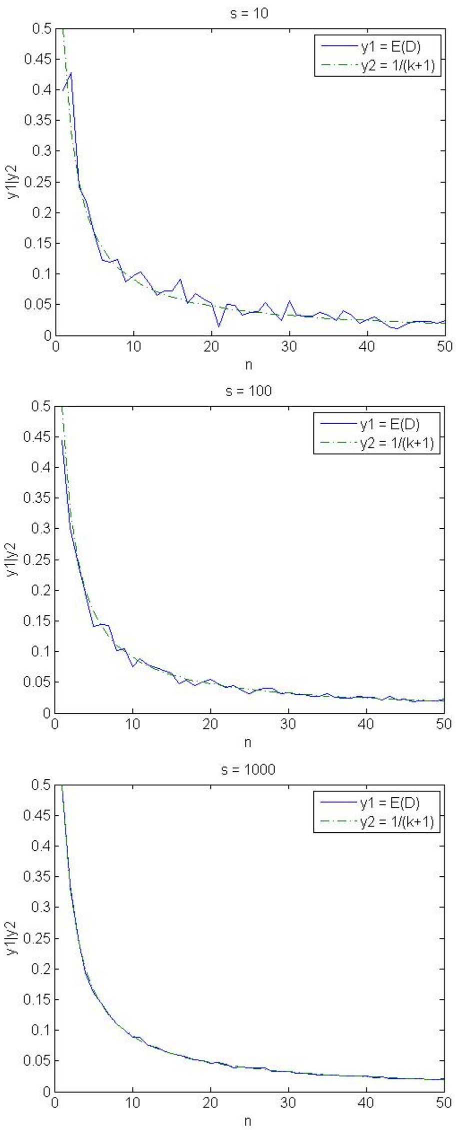


Figure 5.1.2: The value of $E(D)$ under various settings.

5.2 The influence of *n*

As discussed in 4.4, the $E(D)$ decreases rapidly as n increases. Figure 5.2.1 shows the simulation on this discussion. The x-axis is n, and the y-axis is $E(D)/b$. As k increases, $E(D)/b$ decreases exponentially. We repeat three times for various value of p_a, the results are similar.

This simulation shows that *tk*-coverage is very efficient for a WSN with large n, the number of nodes covering one position at one time. The parameter n in practical deployment varies in different applications. In addition, notice even when p_a is not very small, for example, p_a=0.5 in figure 5.2.1, $E(D)/b$ decreases exponentially due to the characteristics of *tk*-coverage. Therefore, for networks that are sensitive to energy utilization, a larger n will greatly reduces the delay.

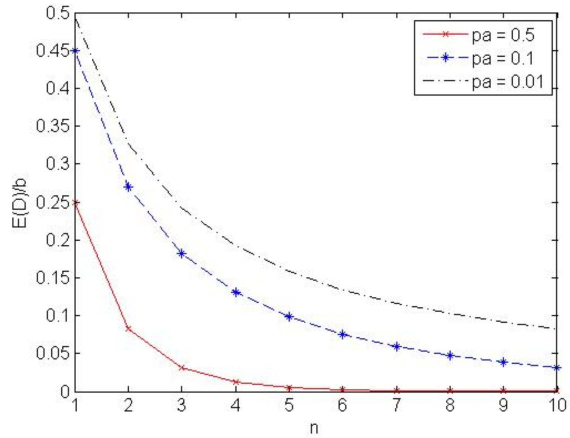


Figure 5.2.1: The influence of n.

6. Conclusion

tk-coverage is a novel concept that is fundamentally different from the traditional *k*-coverage. Sensor nodes apply periodical sleeping strategies for energy saving. By using the time dimension, TKC can achieve energy efficiency with acceptable detection latency. In addition, different sleeping strategies can be used to satisfy different application requirements. We analyze the tradeoff between the energy utilization and time delay, as well as the influence of other network settings. Simulations are conducted to validate our design. TKC has demonstrated its great potential for energy efficient monitoring.

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