

DyKCo: Dynamic k -Coverage in Wireless Sensor Networks

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Abstract— In Wireless Sensor Networks maintaining complete coverage over an area is one of the fundamental problems. The network must be able to provide the requested coverage while maximizing the network lifetime through scheduling sleep for extraneous nodes. The network should also be able to configure itself to provide different levels of coverage for different applications. In this paper we present DyKCo, a probabilistic method to provide dynamic k -coverage on the area of an event. Our proposed method creates 1-coverage on the whole sensing area and creates k -coverage on the area of a detected event. Our simulations show that we can achieve very high energy savings and high coverage which result in longer network lifetime and higher accuracy. Due to probabilistic nature of our approach it needs much less communication than similar methods to provide k -coverage.

Keywords— k -Coverage, Wireless Sensor networks, Sleep Scheduling, Intelligent Sensor

I. INTRODUCTION

Use of Wireless Sensor Networks with large number of low-power, short-lived, unreliable sensors for a wide-range of potential applications such as battlefield surveillance, machine failure diagnosis, biological detection, home security, smart spaces, inventory tracking, etc [1], [2], [3] has attracted a great deal of research attention. These nodes usually have a low-bandwidth wireless radio for communication.

Sensor nodes usually work with small low power batteries as the source of energy. Individual nodes [4] can last only 100-120 hours on a pair of AA batteries in the active mode [26] and Battery capabilities are only doubled every 35 years [11]; therefore, power efficiency is the main challenge in sensor network applications.

Putting sensors to periodic sleep in dense sensor networks has been suggested as a way to increase the network longevity [25]. Sensor nodes in the sleep mode consume only 0.1% of the energy consumed in the active mode [4].

Several methods for putting nodes into low duty cycle have been proposed [5], [6]. But inactive nodes cause higher delay, lower coverage and connectivity in exchange for power efficiency. Nodes in the sleep mode are unable to detect events in their sensing range and are unable to receive or forward any packets (in case only the transmission device is turned off detection is possible). Sleep scheduling addresses this problem.

Several scheduling schemes have been suggested to minimize the effect of sleeping nodes on the desired parameter (delay, connectivity, etc) in the network [7], [8], [9]. Coverage is one of the important parameters that is affected by the scheduling scheme.

How well an area is covered can be considered as a measure of Quality of Service (QoS) and is subject to a wide range of interpretation due to large variety of sensor networks' applications [10].

In surveillance and monitoring applications, it is usually required to have at least k sensors cover each point in the surveillance zone (k -Coverage). In dense networks [11] where there are more than k sensors in each area, putting sensors to low duty cycle for energy saving, raises the question of which nodes should be active in order to maintain the same coverage [4], [12]. It means that we need a coordination function [13] between neighbor nodes to determine the state of each node in each cycle in a way that the total number of sensors to cover the neighborhood is approximately k .

Reasons for requiring k -coverage [4] include:

Classification of an intruder (person, soldier, vehicle), making sure that the alarm messages reach the base station (considering high packet loss probability in wireless sensor networks [14]), detection of false alarms due to natural phenomena or an internal error in the sensor [15], and more accuracy in estimation of target location and velocity by a factor of \sqrt{k} .

The need for a mechanism to dynamically configure the coverage provided according to the needs of the application is mentioned in [9]. Dynamic configuration of sensor network helps the network to adapt to different applications' requirements and maximizes the energy efficiency.

In this paper we present a probabilistic approach for creating dynamic k -Coverage. DyKCo creates coverage (1-coverage) over all the surveillance zone and k -coverage only on the event(s).

DyKCo saves a lot of energy since generally it wakes only 1 node instead of k -nodes in each area (in case of a detection this number is increased to k nodes in that area). Also computational and messaging overhead of this approach for

providing coverage is much lower than similar approaches presented in [9],[16],[17].

Use of MAC protocols such as S-MAC [5] or T-MAC [6] that support energy saving and sleep scheduling mechanisms is necessary. These MAC protocols provide synchronous wake ups in the neighbor nodes which will be discussed latter in this paper.

The rest of this paper is as follows: In section II we discuss the related works. We review several methods proposed to provide the coverage requested by the applications. We also discuss the assumptions, advantages, and disadvantages in some of these methods. In section III, our novel method to provide dynamic k -coverage on the events is introduced. We also introduce the necessary MAC support for our methods. Also, we introduce the *Misplaced k -Coverage problem*. In Section IV we present our analysis of the energy consumption and provided coverage of our method. In section V, our simulation results are presented and we justify our results. Our conclusions are discussed in section VI.

II. RELATED WORKS

[16]Reference [16] presents a deterministic method for providing coverage on the surveillance zone. This method guarantees that the original sensing coverage is maintained after the redundant nodes are turned off. This approach assumes that all nodes have *location information*. It also requires techniques to estimate the direction of the received signal which may require more than one antenna. Moreover, each node requires a mechanism to acquire its neighbors' location information.

A recent work [18] discusses how the probability of k -coverage changes with sensing radius and number of sensors deployed in different distributions (Poisson point process or uniform point process). Authors take the *boundary effect* into account. Nodes are always active and no sleeping period is considered.

Reference [15] and [19] report the results on actual deployments of wireless sensor networks that provide us with key lessons on detection, classification, fault models (Node failure, communication faults, etc), capability of radios, false alarms, energy consumption in different modes, etc.

Reference [12] addresses the *Set K -Cover* problem in which we are given a finite set of areas, and the objective is to partition sensors into covers such that the number of covers that include an area, summed over all areas, is maximized. In fact the number of times the areas are covered is maximized. This means that by rotating between k covers more than a certain percentage (e.g. 80%) of the areas is covered within the sliding window of k previous time steps; therefore coverage is not preserved. [20] solves the maximum set covers problem when a set of known targets are monitored. It also proves that maximum set covers problem is *np-complete*.

Reference [9] shows that in order to have connectivity in a sensor network that has 1-coverage over an area, communication range should be equal to or more than twice the sensing range ($2R_s \leq R_c$). It also presents a method for guaranteed connectivity and coverage which can provide

different degrees of coverage. [17] present a distributed algorithm for density control in wireless sensor networks through local probing of its neighbors. It does not require location and topology information of its neighbors.

Reference [21] presents a method to calculate the coverage provided over each area in the network which can be used to determine which areas are not sufficiently covered.

Most deterministic methods such as [9],[16],[17] use an *eligibility rule* to turn redundant nodes off in the area. In order to determine which nodes can be turned off they require the location information of their neighbors or they need to probe the area for other active sensors. This imposes a higher communication and computation overhead in comparison to probabilistic approaches. To the knowledge of authors the only attempt to dynamically configure the sensor network to provide different level of coverage has been made in [9]. Deterministic methods are usually unable to provide dynamicity due to very high overhead (communication, computation) and/or high response time.

In [4], boundary conditions to have k -coverage in a mostly sleepy network in three distributions (Grid, Random Uniform, Poisson) are presented. We use the equations presented in [4] to dynamically calculate the probability of waking in the sensor nodes which is discussed further below.

III. DYNAMIC K-COVERAGE

A. Problem Definition and Assumptions

We have a set of N sensors $S = \{s_1, s_2, \dots, s_n\}$, in a two dimensional area A . Sensors are distributed using Random Uniform Distribution, Grid Distribution or Poisson distribution. All sensors have the same sensing range r .

Also as shown in Fig. 1 sensor nodes support Sleep/Awake periods.

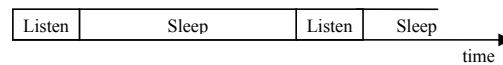


Figure 1. Sensor Nodes Duty Cycle

Sensor nodes in the sleep period can turn off their sensing device and their transmission device to maximize the energy saving (nodes in listen mode consume nearly as much energy as the receive mode [13]). Turning transmission device on or off is controlled by the MAC protocol and the sensing device is controlled by the wakeup probability which we will discuss later in this paper.

Our assumption are very similar to [11][4]. Our network is very dense (such that the number of sensor nodes deployed may be orders of magnitude higher than the working nodes) and sufficient sensor nodes are deployed [4] to achieve the desired k -coverage. Our sensor nodes are synchronized using one of the techniques to provide micro-second level time synchronization [22], [23]. We assume that probability of parallel occurrence of events in the network is relatively low, since if there are many events that need to be monitored constantly, dynamicity of coverage is pointless. Sensor nodes radios have different energy consumption in off, listening,

receiving and transmission modes [13][15]. We assume that nodes do not have any location information. Also nodes do not have any information about their neighbor's locations or states. Sensing range of the all nodes is the same and communication range is equal or more than sensing range. Moreover, we assume if an intruder is in sensing range of an active sensor it will definitely be detected.

We propose a method to provide 1-coverage over the entire surveillance zone. Number of nodes that cover an area is increased to k in case an event is detected by the only active sensor in that area. Since we don't want to use any location information or control messages to provide 1-coverage we use a probabilistic approach to locally set the state of each node in each cycle. To determine the sleep probability of each node we use the equations presented in [4].

Consider that a function $\phi(np)$ is slowly growing if it is monotonically increasing and $O(\log \log(np))$, and goes to infinity as $n \rightarrow \infty$. Let $c(n) = \frac{np\pi r^2}{\log(np)}$

For the Random Uniform Distribution and Poisson Distribution, for some $\phi(np)$ if

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

Then all the points are almost always k -covered as n approaches infinity[4]. Where n is the number of sensors deployed, p is the probability of being active in each cycle, r is the sensing radius of each sensor, and k is the level of coverage.

For Grid Distribution for some $\phi(np)$ if

$$c(n) \geq 1 + \frac{[\phi(np)(1 + \sqrt{p \log(np)}) + k \log \log(np)]}{\log(np)} \quad (2)$$

Then all the points are almost always k -covered as n approaches infinity. [4]

Similar to [4], we assume that number of deployed sensors in the network is sufficiently large; therefore the boundary conditions (1) and (2) hold. We use these boundary conditions to calculate the wakeup probability of nodes (for a fixed number of deployed nodes) regarding different levels of coverage.

Our goal is to find the minimum probability that satisfies the above boundary condition. Minimizing the probability results in lower number of active nodes in each cycle which results in higher energy saving. Of course higher probabilities are also acceptable, they are less energy efficient, but provide higher coverage. Using higher probabilities is sometimes necessary to meet the criteria of the application as we will see in the next section. We use these boundaries to determine the probability required to have 1-coverage all over the area and provide k -coverage on an event detected in the network.

B. DyKCo, Our Approach

As shown in Fig. 2, our goal is to have (at least) one active node in all the areas to completely cover the surveillance zone. We use the conditions in III.A to set the probability of

awakening in the nodes. All nodes should have the distribution type and number of the deployed sensor nodes in order to be able to calculate the wakeup probability for 1-coverage. To calculate the required wakeup probability to achieve k -coverage the required k should be also flooded in network. These parameters should be flooded in the network only once after it has been deployed. In case there is a change in these parameters, for example, if the required k or the number of deployed nodes is changed (using the same distribution) we need to re-flood these parameters in the network. All nodes after receiving these parameters calculate the sleep probability required for 1-coverage and k -coverage and store them.

All nodes primarily set their sleep probability to 1-coverage level; therefore, since the surveillance zone is 1-covered when an intruder enters the area, it is detected by at least one sensor. The node that has detected the intruder waits until the end of the sleep period of its neighbors and sends a broadcast message alerting others about the intruder.

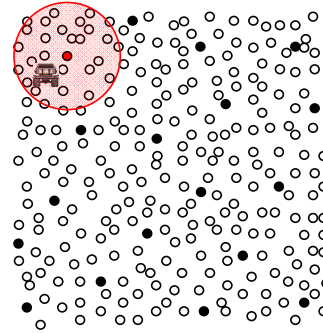


Figure 2. A Random Uniform Distribution of Sensor nodes, The area is 1-covered, By detecting an intruder the active sensor node in the area sends a broadcast message (filled circles are active nodes in this period).

Nodes that receive this broadcast message increase their wakeup probability to the k -coverage level. Therefore in the next duty cycle the number of active nodes in the area is increased to approximately k nodes (Fig. 3).

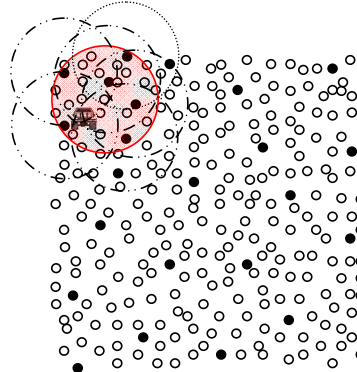


Figure 3. In the next cycle the number of active nodes is increased to k (in this case 5) nodes. The rest of the network preserves the 1-coverage.

All active nodes in this cycle that detect the intruder send a broadcast message at the beginning of the next cycle. In case an active node with wakeup probability level k -coverage doesn't detect an intruder it reduces its probability level to 1-coverage (Fig. 3).

C. Misplaced k -Coverage Problem

Since only nodes that are in the communication range of the first node which has detected the intruder can hear its broadcast message and set their wakeup probability to k -coverage level, we may have less than k sensors cover the intruder (As shown in Fig. 2 we have 4 nodes cover the intruder instead of 5).

All the nodes that should set their wakeup probability to k -coverage level are not able to hear the broadcast message (Fig. 3). Also the intruder may move before the beginning of the next cycle; therefore even less sensors may cover the intruder. We call this problem the *misplaced k -coverage problem*.

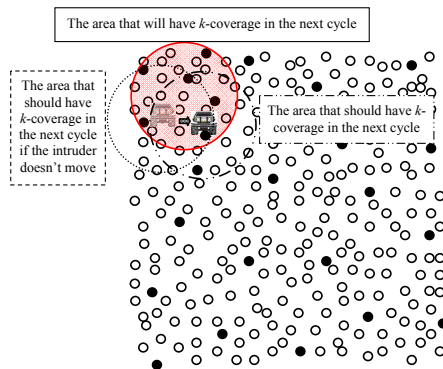


Figure 4. Misplaced k -Coverage problem.

To address this problem, in a pessimistic guess we consider that only half the nodes in the *effective area* (the area that should actually have k -coverage) can hear the broadcast messages that nodes which has detected the intruder in the last cycle, send. This is a pessimistic guess since speed of intruder is relatively slow in comparison to the sensing range and duty cycle of nodes. This assumption causes the nodes to calculate higher wakeup probability for the k -coverage level which results in higher coverage (sometimes two or three time more) in the area within the communication range of the broadcast message and nearly k -coverage on the moving intruder (Fig. 5).

Both our simulations and simulation results in [4] (static k -Coverage) show that the actual coverage over the surveillance zone is somewhat lower than the $k_{analysis}$; Therefore this assumption helps achieve a closer coverage to the desired coverage.

Since as n approaches infinity, $n/2$ also approaches infinity the conditions (1) and (2) still hold. Also $\mathcal{O}(np)$ is $\mathcal{O}(\log \log(np))$; Therefore, this change does not create dramatic changes in the calculated p , but gives us enough higher coverage (in exchange for lower energy efficiency).

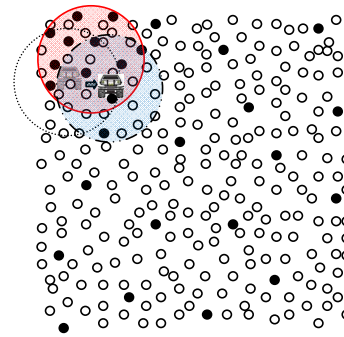


Figure 5. Solution to misplaced k -coverage problem, The intruder is covered by 6 sensors.

D. MAC Support for our Method

Our approach needs support from the MAC layer. MAC layer should support energy saving modes (Active/Sleep modes). S-MAC [5] and T-MAC [6] support such modes. The duty cycle of S-MAC is shown in Fig. 6.

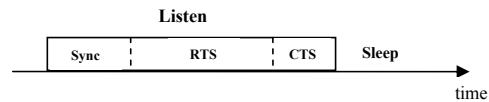


Figure 6. S-MAC Duty Cycle

Since we use broadcast messages to alert neighbor nodes about the intrusion we need all the neighbor nodes to be active at the end of each cycle. S-Mac provides such synchronized duty cycles between neighbor nodes.

In the SYNC period nodes exchange their sleep schedules so that neighbor nodes wake up at the same time to be able to exchange data messages.

In Data time (RTS/CTS period) nodes use a contention based algorithm similar to 802.11 to reserve the medium for themselves. Those who were able to reserve the medium start exchanging data messages at the start of next sleep period. Other nodes turn off their transmission device. (For further description please refer to [5], [6]).

Since after the initial synchronization period the SYNC period is rarely used (to resynchronize the schedules) we use this period for our broadcasts. In case there is a SYNC packet waiting to be send we can piggy back our ALERT on the SYNC message. Otherwise an independent ALERT message is created and sent (RTS/CTS period can be similarly used).

In case the MAC protocol of our choice doesn't support synchronized wakeups of neighbor nodes to send the broadcast messages, in order to ensure that all neighbor nodes hear the broadcast message, the node has to wake up at the wakeup time of each one of its neighbors (similar to [24]) and rebroadcast the ALERT message which increases the energy consumption.

E. Why not the maximum possible coverage?

We can wake every node in the neighborhood of the first node that has detected the intruder to maximize the coverage on

the intruder. The first reason this is not desirable is energy efficiency. We only need to provide requested coverage from our application. More coverage is considered as a source of energy loss. The second reason is collision avoidance. As the number of nodes that detect the intruder increases the probability of collision of the data and broadcast packets of neighbor nodes also increases.

IV. ENRGY CONSUMPTION AND COVERGAE ANALYSIS

Our approach presents a new method to provide dynamic k -coverage over an intruder in the surveillance zone. Since we only provide k -coverage in the area of the intruder and the rest of surveillance zone is 1-covered the number of active nodes in each cycle is greatly reduced. According to our simulations we only keep nearly half the number of active nodes in each cycle in comparison to the number of active nodes in the static approach where the entire surveillance zone is k -covered. Also since we calculate higher wakeup probability to solve the *misplaced k-coverage problem* the average coverage provided on the intruder is usually higher than the static method. Increasing the number of deployed nodes without changing the required k directly increases the network lifetime since the number of active nodes in each cycle which are supposed to provide 1-coverage over a surveillance zone is fixed. The cost of the broadcast messages sent to alert the neighbors is fairly low; because the ALERT message is a small packet and in case there is a SYNC message it can be piggybacked. The overhead of calculating the wakeup probability is also fairly low since the probability levels only need to be calculated once. Also if tighter boundary conditions in comparison to conditions (1) and (2) are found we can easily replace these boundaries to calculate the required wakeup probability. Since DyKCo is a probabilistic approach it doesn't need any location or probing information unlike [9],[16],[17] to provide the requested coverage. This approach can be considered stealthy [25]. Also DyKCo is compatible with current popular MAC protocols in wireless sensor networks.

V. SIMULATION RESULTS

In our simulations we deploy sensors in an area of size 150m x 150m. Sensors' sensing and communication radius is 4m. If nodes have higher communication range than sensing range the number of nodes that wake up in case an intruder is detected, will be higher which results in higher coverage and lower energy efficiency.

Static k -coverage calculates the probability needed to achieve k -coverage according to [4]. All nodes have the same probability of waking. We compare this method to our method in minimum coverage, and average coverage provided over the intruder. We also compare average number of active nodes in each cycle between these methods. We use the boundary conditions (1) and (2) for our dynamic method in two ways, in the first one (DyKCo) we use the original number of deployed nodes and in the second one (DyKCo with $n/2$) we use half that number to calculate wakeup probability.

The average minimum coverage achieved in 10 runs for each deployment of the sensor network for each method is shown in Fig. 7. The requested coverage was 8-coverage.

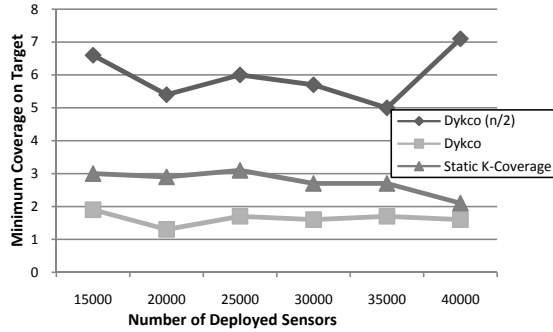


Figure 7. Average minimum coverage over the target

Fig. 7 shows that as expected the coverage achieved in the dynamic method with half the number of deployed nodes has the highest average minimum coverage. Static k -coverage provides lower coverage. The dynamic method without considering *misplaced k-coverage problem* has the lowest coverage. The *misplaced k-coverage problem's* effect is clear.

Fig. 8 depicts the average number of active nodes in different methods. As shown in Fig. 8 number of active nodes is almost always fixed. This means to have k -coverage in the area of sensing we need a fixed number of sensor nodes. This also means that adding more nodes directly increases the network longevity.

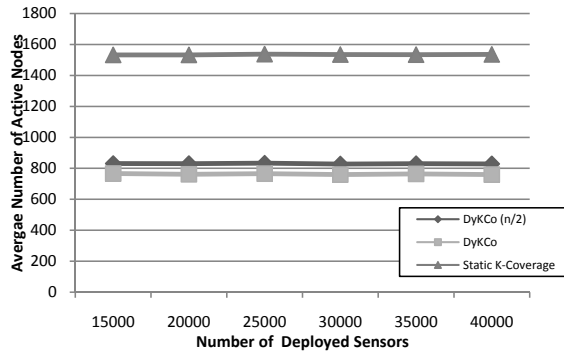


Figure 8. Average number of active nodes in each cycle

The number of active nodes in the dynamic method is nearly half the number of active nodes in the static method.

Average coverage on the intruder in 10 runs of the simulation for each method with different number of sensors is presented in Fig. 9. Average coverage provided is much higher than the requested coverage. This shows that assuming that nearly half the nodes in the *effective area* of the intruder are unable to hear the ALERT message is a pessimistic guess.

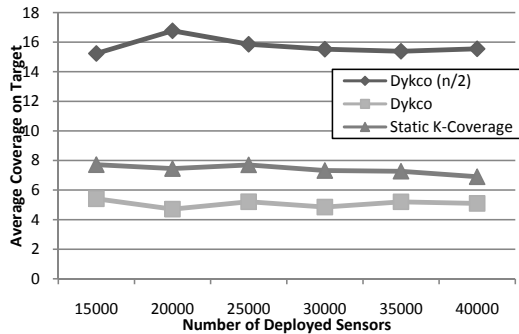


Figure 9. Average coverage on the target

The number of active nodes is a very good measure of energy consumption of each method. Based on our simulation results we can achieve nearly 50% energy saving by using the presented methods.

VI. CONCLUSION

In this paper we presented a novel method to provide dynamic k -coverage over an intruder in a surveillance zone using wireless sensor networks. DyKCo is a probabilistic approach which provides 1-coverage over the area and in case an intruder is detected increases this coverage to k -coverage. Our simulations show dramatic improvement in coverage and energy consumption of the network which results in higher accuracy and network lifetime. DyKCo is completely compatible with current popular MAC protocols in wireless sensor networks. In this approach nodes do not need any location information and due to its probabilistic nature, minimal communication to provide k -coverage is needed.

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