Optimal Barrier Coverage Scheduling and Attack Detection under Mobile Sensors

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Abstract— Surveillance monitoring is performed using the sensor devices. Capture, store and transmission are the main operations of sensor devices. Temperature, humidity, density of carbon dioxide and pressure details are captured by sensor devices. Battery power is the main limitation of sensor devices. The intrusion detection system identifies the legitimate and attackers in the network area. The intrusion detection system is designed in two categories. In the first model a system component is used for monitoring the security of a WSN and diagnosing compromised/vulnerable. Second model is the monitoring or surveillance system for detecting a malicious intruder that invades the network domain. Sensor mobility schemes are applied with barrier coverage details. Dynamic Sensor Patrolling (DSP) mechanism is used to manage sensor mobility with availability levels. Periodic monitoring scheduling (PMS) algorithm is used to monitor each point along the barrier line periodically by mobile sensors. Coordinated sensor patrolling (CSP) algorithm is used to improve the barrier coverage. Sensor mobility and intruder arrival information are used to enhance the barrier coverage in CSP. In CSP each sensor's current movement strategy is derived from the information of intruder arrivals in the past. Simple Distributed Coordinated sensor patrolling (S-DCSP) and General Distributed Coordinated sensor patrolling (G-DCSP) schemes are used in the scheduling process. Clustering process is used in the G-DCSP scheme. Optimal coverage scheme is introduced to manage scheduling of K barrier coverage environment. Distributed scheduling and intrusion detection is performed with predefined sensor count values. The system is enhanced to handle different intruder arrival models. Sensor movement is rescheduled with intruder arrival information.
Key words: CSP, DSP, G-DCSP

I. INTRODUCTION

Wireless Sensor Networks (WSNs) are composed of a large number of sensor nodes; therefore, an algorithm for a WSN is implicitly a distributed algorithm. In WSNs the scarcest resource is energy and one of the most energy-expensive operations is data transmission. For this reason, algorithmic research in WSN mostly focuses on the study and design of energy aware algorithms for data transmission from the sensor nodes to the base stations. Data transmission is usually multi-hop, due to the polynomial growth in the energy-cost of radio transmission with respect to the transmission distance. The algorithmic approach to WSN differentiates itself from the *protocol* approach by the fact that the mathematical models used are more abstract, more general, but sometimes less realistic than the models used for protocol design.

Modern mobile phones come with a variety of sensors that automate or easy many of our daily tasks. This field takes into account the presence of an accelerometer, a gyroscope, a compass, and a barometer. Accelerometers in mobile phones are used to detect the orientation of the phone. The gyroscope, or gyro for short, adds an additional dimension to the information supplied by the accelerometer by tracking rotation or twist. An accelerometer measures linear acceleration of movement, while a gyro on the other hand measures the angular rotational velocity. Both sensors measure rate of change; they just measure the rate of change for different things. In practice, that means that an accelerometer will measure the directional movement of a device but will not be able to resolve its lateral orientation or tilt during that movement accurately unless a gyro is there to fill in that info. With an accelerometer you can either get a really "noisy" info output that is responsive, or you can get a "clean" output that's sluggish. But when you combine the 3-axis accelerometer with a 3-axis gyro, you get an output that is both clean and responsive in the same time." The digital compass that's usually based on a sensor called magnetometer provides mobile phones with a simple orientation in relation to the Earth's magnetic field. As a result, your phone always knows which way is North so it can auto rotate your digital maps depending on your physical orientation. And finally, you may see a device sporting a barometer in its specs sheet. Contrary to what you may suggest, it has nothing to do with weather. Instead, the barometer is there to help the GPS chip inside the device get a faster lock by instantly delivering altitude data.

II. RELATED WORK

We introduce the recent results on barrier coverage. Please refer to [11], [12] for results on other types of coverage. S. Kumar et al. introduced the concept of barrier coverage. They defined the notion of k-barrier coverage and proposed algorithms to decide whether a belt region is k-barrier covered or not after sensor deployment. The barrier coverage problem is very difficult to solve in a decentralized way due to its globalized nature. Chen et al. [6] addressed this challenge by introducing the concept of local barrier coverage. Although local barrier is not equivalent to global barrier in general, they showed that it does approximate global barrier in some cases like extremely thin belt regions.

Liu et al. [1] proposed a distributed algorithm to construct multiple disjoint barriers for strong barrier coverage when sensors are distributed thin belt area of irregular shape and have the advantages of reduced delay and communication overhead compared with a centralized solution. Chen et al. [7] investigated the quality of barrier coverage. Their work can identify when the barrier performance is less than a predefined value and where a repair is needed. Saipulla et al. [8] studied the barrier coverage problem when sensors are deployed along a line. The tight lower-bounded probability of the existence of

barrier coverage was derived. Yang and Qiao [9] studied the weak barrier coverage by exploiting the sensing collaboration between sensors.

In mobile sensor networks, node mobility has been exploited for autonomous barrier coverage formation and improvement. Saipulla et al. [4] studied how to relocate sensors with limited mobility to improve barrier coverage after random sensor deployment. They investigated the effects of the density and mobility of sensors on the barrier coverage improvement and proposed an algorithm to check the existence of barrier coverage. Shen et al. [2] studied energy-efficient sensor relocation. A centralized algorithm was proposed to compute the optimal positions for all sensors to form barrier coverage, provided that the initial positions of the sensors are known as a prior. Bhattacharya et al. addressed how to optimally move sensors to the boundary of the ROI to form barrier coverage. Keung et al. [5] focused on providing k-barrier coverage against moving intruders. They adopted the classical kinetic theory of gas molecules to analyze the inherent relationship between barrier coverage performance and a set of network parameters such as sensor density and intruder mobility. Bisnik et al. considered a scenario where stochastic events arrive at a collection of discrete points along a closed curve and investigated how the event staying time impacts the event capture performance. They did not consider the temporal correlation between events.

III. COVERAGE MANAGEMENT IN WSN

Due to real operational limitations such as human inaccessibility, sensors are usually deployed randomly, e.g., dropped by an airplane, in or near a region of interest (ROI). Random sensor dropping causes the WSNs to have topological weaknesses such as sensing holes, communication bottlenecks and network partitions. Mobile sensors, integrating advanced robotics and sensing technologies, have recently developed to overcome these drawbacks. Unlike traditional static sensors, they have locomotion and are thus able to autonomously improve network performance by adjusting their initial positions to desired ones [3],[10].
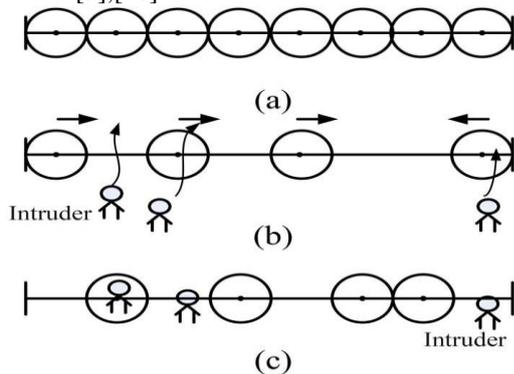

Fig. 1: (a) Full Barrier Coverage by Static Sensors. (b) and (c) Barrier Coverage by Mobile Sensors.

Sensors are not designated to monitor events inside the ROI but to detect intruders that attempt to penetrate the ROI. A real-life example is to deploy sensors on the boundary of a country's territory to identify and prevent illegal entrance to the country. Because sensors are placed within a thin belt region along the ROI boundary acting like a barrier to intruders, the coverage provided by them is referred to as *barrier coverage* [5]. Existing solutions to barrier coverage in mobile sensor networks implicitly assume the availability of sufficient sensors. They focus on how to move the available sensors one time to construct as many barriers as possible with a minimum aggregate moving distance [4]. These solutions fail to work if a single barrier cannot be formed no matter how the sensors are moved due to sensor scarcity. This situation is very likely in reality for budget limitation as it is costly to equip a large number of sensors with locomotion. Therefore, it is highly desirable in practice to design a cost-effective barrier coverage, i.e., using mobile sensors as few as possible to meet the Eight sensors are needed to form a complete barrier according to Fig. 1(a). If only four sensors are available as depicted in Fig. 1(b), a complete barrier cannot be formed by moving each sensor only once. This is illustrated in Fig. 1(c) where the four sensors reach their final positions by the one-time movement indicated by the arrowed lines in Fig. 1(b), with inevitable coverage holes that render some intruders undetected. To improve the barrier coverage performance, it would be better to let mobile sensors patrol along the line dynamically, so that each sensor can be present for intruder detection at different locations with different time.

It is a challenging task to design sensor patrolling algorithms for achieving desirable barrier coverage performance. From Fig. 1(b) and (c), there are three intruders trying to cross the barrier line and sensors have no idea about their arrivals and trajectories. If the sensors move in the directions displayed in Fig. 1(b), only one intruder can be detected in Fig. 1(c).

We consider the barrier coverage problem where m sensors are needed to guarantee full barrier coverage and there are only n mobile sensors available ($n < m$). We first model the arrival of intruders at a specific location as a renew process, in which the next intruder's arrival time is correlated with the current one. The barrier coverage performance is characterized by average intruder detection probability. We formulate the problem as a dynamic programming problem where the movement strategy of all sensors should be made in each time slot dynamically to maximize the intruder detection probability, based on current locations of sensors and intruder arrival information collected in the past time slots. We propose two sensor patrolling algorithms to solve this problem: periodic monitoring scheduling (PMS) and coordinated sensor patrolling (CSP). In PMS, each point of interest in the barrier line is periodically monitored by sensors n times every m time slots, while in CSP the probability of intruder arrival at each point is calculated dynamically and a coordinated movement strategy is derived accordingly. We then generalize our results to work for other intruder arrival models such as Markov chain.

IV. COORDINATED SENSOR PATROLLING (CSP) SCHEMES

We present a periodic monitoring scheduling (PMS) algorithm to solve the barrier coverage problem. PMS is easy to implement and is featured with absence of coordination among sensors. Recall that there are m points and we only have n, $n < m$ mobile sensors to monitor these points. During each time slot, there will be $m - n$ points that are not monitored by any sensor. The basic idea of PMS is

to let sensors monitor points periodically. Let T denote the number of continuous time slots that a sensor will stay after it reaches another point. In PMS, initially a designated sensor moves to point j, $j = 1, 2, n$ and stays there for T time slots. Afterwards, the sensor at point j moves to point mod $(j + n, m)$ and stays there for T time slots. The process continues until all the sensors run out of energy.

Let $m' = \dfrac{m}{\gcd(m.n)}$, where $gcd(\cdot)$ is the greatest common divisor function. In PMS, the minimum scheduling period is m_T. During every m_T time slots, each point j is monitored by sensors for $n' = \dfrac{n}{\gcd(m,n)}$ time slots. The ratio of the number of time slots during which there is a sensor monitoring point j to the total number of network operation time slots is therefore $\dfrac{n}{m}$. An illustration of PMS ($m = 5$, $n = 3$ and $T = 1$). The algorithm is sketched in Algorithm 1.

According to PMS algorithm, sensor at point j will move $2r_s n$ distance to another point j', j'= mod (j + n,m), when j + n ≤ m and $2r_s (m - n)$ distance when j + n > m. For every m' T time slots, a sensor will move $2r_s (m - n)$ distance for n' times and $2r_s n$ distance for m' − n' times. Therefore, the average sensor moving distance L is

$$L = \frac{n' \times 2r_s(m-n) + (m'-n') \times 2r_s n}{m'T} = \frac{2r_s(mn' + nm' - 2mn')}{m'T}$$

1) Initially:
Assign each sensor a unique ID $i \in [1, n]$
Assign each point a unique ID $j \in [1, m]$
2) At time slot t = 0:
Let sensor i move to point i
3) At time slot t = t + T:
For every point j, the sensor at point j moves to point jt, where $jt = Mod(j + n, m)$.
4) Terminate if all sensors run out of energy.
Algorithm 1 Periodic monitoring scheduling (PMS)

A. Simple DCSP (S-DCSP):

S-DCSP consists of two phases: i) an initialization phase and ii) a dynamic movement phase. The sensors are assumed to be connected and one of them is elected as leader. The leader is responsible for distributing the preference level of each sensor among the points, indicating how the sensor likes to monitor the points. It first sorts all the points according to their positions along the barrier line. Then it performs preference distribution for all the sensors one by one, in the increasing order. For sensor i, $1 \leq i \leq n$ (the i-th sensor), the leader assigns a preference level $0 \leq plj_i < 1$ to point j, $1 \leq j \leq m$ (the j-th point) sequentially in the increasing order, subject to the constraint $\sum_{i=1}^{m} pl_i^j = 1$.

B. General DCSP (G-DCSP):

In the dynamic movement phase, each sensor i moves between points in MSi. For each point j, j MSi, sensor i maintains the number of time slots, denoted by Iij, for which it has not monitored point j since its last visit. At the beginning of each time slot, sensor i makes decision whether to move and where to move. It will decide to stay at its current point if it did not detect an intruder at the last time slot, or move to another point otherwise. In order to find a

new point to move to, sensor i calculates the intruder arrival probability $q Iij t$ for every point j, j MSi. The point with the largest $plj I \times q Iij t$ is selected. Once the movement destination is determined, it moves immediately and stays there for the current time slot.

V. WSN COVERAGE MANAGEMENT ISSUES

Barrier coverage models are used to decide movement of individual sensors to construct many barriers. Dynamic Sensor Patrolling (DSP) mechanism is used to manage sensor mobility with availability levels. Periodic monitoring scheduling (PMS) algorithm is used to monitor each point along the barrier line periodically by mobile sensors. Coordinated sensor patrolling (CSP) algorithm is used to improve the barrier coverage. Sensor mobility and intruder arrival information are used to enhance the barrier coverage in CSP. In CSP each sensor's current movement strategy is derived from the information of intruder arrivals in the past. Simple Distributed Coordinated sensor patrolling (S-DCSP) and General Distributed Coordinated sensor patrolling (G-DCSP) schemes are used in the scheduling process. Clustering process is used in the G-DCSP scheme. The following problems are identified from the existing system.
- Two barriers level base sensor movement
- Average intruder detection probability is low
- The system handles limited intruder arrival models
- Sensor node requirement is high

VI. OPTIMAL BARRIER COVERAGE SCHEDULING AND ATTACK DETECTION

The mobile sensor scheduling scheme is adapted for K barrier coverage models. Rescheduling process is used to reassign nodes with reference to the intruder arrival details. The scheduling scheme is optimized to handle different intruder arrival rates. The system is divided into six major modules. There are WSN Setup, Clustering Process, Dual Barrier Coverage Scheduling, K-Barrier Coverage Scheduling, Intrusion Detection Process and Rescheduling Process. WSN setup module is designed to construct the wireless sensor network. Clustering process module is used to group the neighbor nodes. Sensor node movement for two barrier coverage is planned under dual barrier coverage scheduling module. K-barrier coverage scheduling module is used decide sensor node movements in K barrier coverage. Intrusion detection process is designed to the Intruders. Rescheduling process is used to reassign the sensor node movement with reference to intruder arrival information.

A. WSN Setup:

WSN setup module is designed to construct the wireless sensor network. Clustering process module is used to group the neighbor nodes.
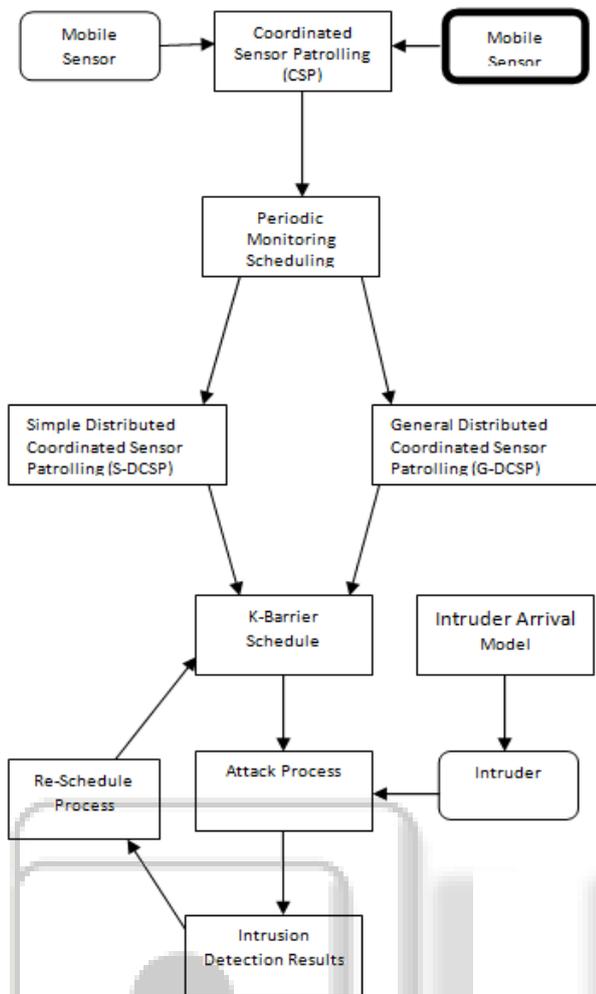
Fig. 2: Architecture of Optimal Barrier Coverage Scheduling Scheme

Sensor node movement for two barrier coverage is planned under dual barrier coverage scheduling module. K-barrier coverage scheduling module is used decide sensor node movements in K barrier coverage. Intrusion detection process is designed to identify the Intruders. Rescheduling process is used to reassign the sensor node movement with reference to intruder arrival information. Wireless sensor network is constructed with node and network area details. Sensor node count and its properties are collected from the user. Monitoring area details are also collected from the user. Node initialization process is performed in the WSN setup process.

B. Clustering Process:

Sensor nodes are grouped into clusters with reference to the coverage details. Sensing coverage and transmission coverage details are used in the clustering process. Cluster head manages the data sensing and transmission process. Cluster head is selected with reference to the resource details. Sensor nodes are grouped into clusters with reference to the coverage details. Sensing coverage and transmission coverage details are used in the clustering process. Cluster head manages the data sensing and transmission process. Cluster head is selected with reference to the resource details.

C. Dual Barrier Coverage Scheduling:

Mobile sensor movement is decided in the barrier coverage scheduling scheme. Dual barrier coverage model assigns a sensor to manage two barrier coverage regions. Distributed coordinated sensor patrolling scheme is used for the scheduling process. Sensor node movement and delay information are assigned in the scheduling process.

D. K-Barrier Coverage Scheduling:

K barrier coverage scheduling scheme is used to assign a sensor node for K coverage regions. Coverage zone is constructed with K barrier coverage regions. A sensor node is assigned for each coverage zone. Sensor node and its neighbor nodes movements are considered in the scheduling process.

E. Intrusion Detection Process:

Intruder arrival analysis is carried out for the attack detection process. Attacker entry is initiated in different coverage regions. The sensor node monitors the coverage region and detects the attacker arrival information. The scheduling scheme is tested with different intruder arrival models.

F. Rescheduling Process:

Sensor node movements are rescheduled with reference to the intruder arrival details. Historical data values are analyzed to estimate the intruder arrival details. Sensor node movement and monitoring delay factors are reassigned. Rescheduling process is verified with different intruder arrival models.

VII. CONCLUSION AND FUTURE WORK

Network monitoring is carried out using mobile sensors. Sensor node movement is scheduled with barrier coverage details. The system is enhanced to manage K-barrier coverage models. Sensor movement rescheduling mechanism is used with intruder arrival details. The system reduces the sensor movement distance in network area. Patrolling time period is minimized in the mobile sensor scheduling scheme. The system improves the intrusion detection accuracy levels for dual and multiple barrier coverage environments. Data collection is achieved with minimum sensors under k-barrier coverage scheme. The system can be enhanced with aggregation based data collection process and data security features.

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