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REVIEW

Deployment schemes in wireless sensor network to achieve blanket coverage in large-scale open area: A review

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Abstract Wireless Sensor Network (WSN) has attracted researchers in recent years due to its wide scope of utility in a future era of automation and remote monitoring. Effective deployment of Sensor Nodes (SNs) is a major point of concern as performance and lifetime of any WSN primarily depends on it. Various models have been proposed by researchers to deploy SNs in large-scale open regions. This article aims at classification, working and comparative analysis of these models.

Contents

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1. Introduction

Sensor is a vital component of any automated system. Wireless Sensor Network (WSN) is a system consisting of a large number of Sensor Nodes (SNs) geographically distributed in the region to be monitored [1–3]. Placement of SNs in the candidate region is the major factor that determines the coverage, connectivity and life of any WSN [4–8]. The application domain of WSN includes disaster management, military surveillance, monitoring of habitat, tracking target, monitoring health of structures, agriculture, intrusion detection and health monitoring [9–17]. Most of the events cannot be sensed from distant locations as SN has limited sensing range (r_s), and this requires SN to be placed at a distance d ($d \leqslant r_s$), from probable location of occurrence of event.

Various schemes have been proposed by the researchers for the deployment of Mobile Sensor Nodes (MSNs), which claims reliable operation with optimal utilization of resources (in terms of number of MSN and time taken for deployment). WSNs are mostly deployed in hostile environments such as volcanoes, flooded regions, and deep oceans [18–20] where human intervention is not possible for post deployment maintenance, so efforts are being made to enhance its efficiency and durability. Deployment can be classified as manual or random. Among these, random deployment from the sky (using aerial vehicle/robot) [21–25] is most suited for unreachable, hazardous or large-scale open environments.

Preferably the term "open area" is used for wide regions such as forests, battlefields, disaster affected regions, and wildlife reservoir which require complete coverage. However, it may also be used to refer small regions exposed to open sky, viz. enemy camps, which require targeted coverage and are not reachable manually.

In this paper various state of art models used for deployment of SNs in large-scale open regions are studied, classified and analyzed.

Rest of the paper is organized as follows. Section 2 describes the classification of deployment schemes used for deployments in large-scale candidate regions. Point initiated relocation schemes are described in Section 3 followed by Random scattering schemes in Section 4. Section 5 describes

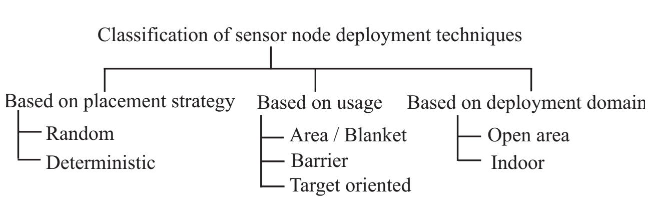

Figure 1 Classification of sensor node deployment techniques.

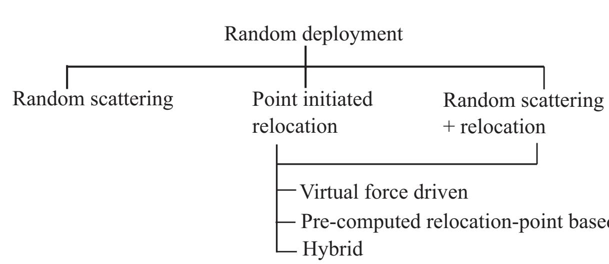

Figure 2 Classification of random deployment schemes based on initial arrangements of sensor nodes.

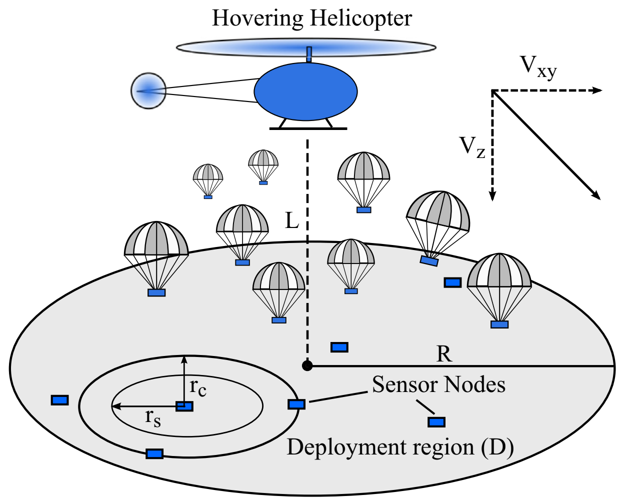

Figure 3 Sensor nodes dropping by hovering helicopter (redrawn from [33]).

random scattering and relocation based deployment schemes. Section 6 discusses about the possible solutions. Finally a conclusion is made in Section 7 after analyzing and comparing various deployment schemes.

2. Classification of deployment techniques

Techniques of sensor node deployment can be classified on the basis of the placement strategy, usage and deployment domain as shown in Fig. 1. However, existing state of art models of deployment can be categorized under multiple classes.

2.1. Open area vs. indoor

Based on the application domain of WSN, deployment can be classified as open area or indoor deployment. Open area deployment is concerned with the placement of SNs in exposed environments where conditions are violent and area to be covered is mostly large (may range from front yard lawn of a few square meters to dense forests of thousands of square km) while Indoor deployment is confined limited domain such as buildings and structures.

2.2. Random vs. deterministic

Area of a candidate region is a major factor that determines the strategy for placement of SNs. Random scattering of SNs from the air is a most common deployment strategy used for deployment in hostile environments or large-scale open regions. However deterministic strategy (point to point) for placement of SNs may be used for small-scale deployments [26–28]. Consider the case of forest fire, which is very common in mountain region of Uttarakhand, India. This scenario can be categorized under large-scale open area, and random scattering strategy to achieve blanket type deployment pattern over the entire candidate region will be most suited to detect forest fire.

Classification tree of random deployment based on initial arrangements of sensor nodes is shown in Fig. 2. In point initiated relocation scheme Mobile SNs (MSNs) are dumped at certain points within a candidate region from where they relocate to most suitable positions. In random scattering schemes SNs are randomly dropped from air. However, it may be accompanied with relocation technique using MSNs to optimize the deployment.

Relocation schemes for MSNs are based on following basic models:

2.2.1. Virtual force driven deployment schemes (VFD)

These schemes exploit the laws of physics to determine the direction of movement of MSNs in order to spread uniformly within a candidate region.

2.2.2. Pre-computed relocation-point based deployment schemes (PRP)

These schemes employ various algorithms to relocate MSNs to the geometrically computed locations in order to spread them uniformly within a candidate region.

2.2.3. Hybrid deployment schemes

These schemes use both of the schemes in different phases for uniformly deploying the MSNs within a candidate region.

2.3. Blanket deployment

Some events may occur randomly within a candidate region at any point and their single occurrence is of great importance. Detection of such events requires complete coverage of the candidate region. Such type of coverage is achieved by blanket deployment.

2.4. Barrier deployment

This type of deployment ensures isolation by encircling the entire candidate region with SNs (i.e., intrusion detection) [29,30].

2.5. Target oriented deployment

Some scenarios have a more precise knowledge of region of occurrence of events (i.e., enemy camps). This type of

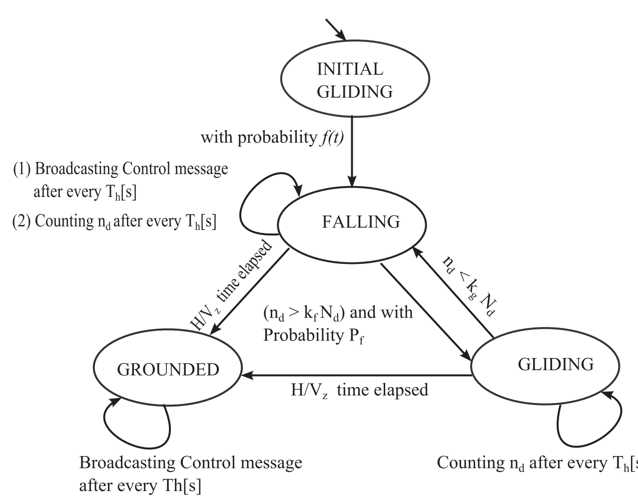

Figure 4 State transition diagram of UAD (redrawn from [33]).

deployment is categorized under target oriented where SNs have to be placed precisely [31].

3. Point initiated relocation

In these deployment schemes MSNs are initially dumped (placed) in a very small area from where they start expanding their vicinity by relocating themselves to cover the entire candidate region.

3.1. Potential field based method

Andrew et al. [32] proposed a Potential Field based method (PFM) for uniformly distributing MSNs in candidate region. PFM was designed, taking into consideration the real time environmental conditions of the candidate region such as obstacles (in the form of buildings, water bodies, etc.). It is mainly concerned with the uniform distribution of SNs within a candidate region. PFM incorporated the feature of self deployment, i.e., all the MSNs are initially spread in very small and they relocate themselves to maximize the coverage. It considers that there exists a potential field that exerts a force of repulsion on MSNs from obstacles and other MSNs. This repulsive force causes the MSNs to spread evenly within a candidate region. Resultant direction of movement of MSNs is the vector sum of all the forces exerted on particular MSN. PFM provides a simple approach for the distribution of MSNs within a candidate region, but extensive MSN movements occur due to oscillations and connectivity with BS is also not guaranteed.

4. Random scattering

It is a common means of deploying SNs in large-scale candidate regions by dispersing them from the sky.

4.1. Uniform Airdrop Deployment method (UAD)

UAD utilizes the floating property of parachutes to distribute dropping SNs within a candidate region. In UAD [33], the authors consider that helicopter hovers above the center of a circular candidate region with radius R at specific altitude H and parachute mounted SNs are dropped from that point as shown in Fig. 3. However, the effect of wind on SNs while dropping is not considered.

An additional device is integrated with parachute to switch its dropping behavior between gliding and falling states. While dropping, vertical velocity of SNs is considered to be V_z which is considered constant throughout its ride (ride is an overall journey of SN before hitting the ground), while the horizontal velocity V_{xy} is accounted for SNs gliding state only and is 0 during SNs falling state. Direction of gliding θ for particular SN remains same throughout the ride once it is determined randomly. It is assumed that $H > R * (V_z/V_{xy})$ so that gliding SNs can reach up to boundaries of D before hitting the ground so as to cover the whole of D. Basic deployment model attempts to distribute MSNs according to Probability Density Function (PDF) for locations of SN within a circular candidate region, which is given by Eq. (1) where polar coordinates are used to specify direction.

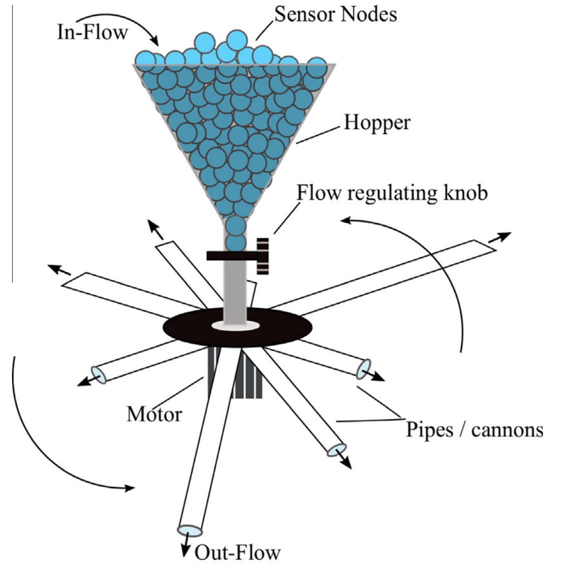

Figure 5 Centrifugal cannon based sprinkler.

$$\int\int_d \frac{1}{\pi R^2} dxdy = \int_0^{2\pi} \int_0^R \frac{r}{\pi R^2} drd\theta \quad (1)$$

where r is the distance moved by particular SN in horizontal direction. PDF of r is given by Eq. (2). Initial time spent by SN before switching to FALLING mode is given by Eq. (3), where u is a uniform random number between 0 and 1.

$$f(r) = \frac{2r}{R^2} \quad (2)$$

$$t_{drop} = \frac{r}{V_{xy}}\sqrt{u} \quad (3)$$

The improved model incorporates inter-SN communication after regular intervals during their ride in order to determine their density over particular region. Mobility parameter m of SNs indicates whether SN is on its ride or grounded. SNs communicate by broadcasting control message regularly after control interval T_c. Possible states of SN during deployment are shown in Fig. 4. After being dropped from helicopter initially

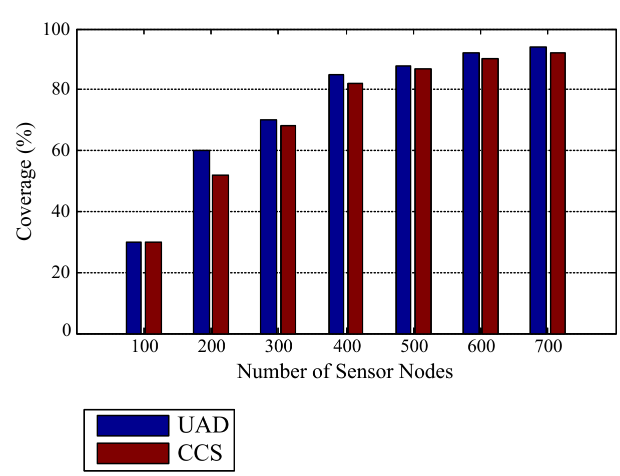

Figure 6 Comparative analysis of random scattering schemes.

Table 1 Comparative analysis of random scattering schemes.

Scheme	sensor type	Scalable	On-node hardware for positioning	Obstacle resistant	Terrain independent
UAD	Static	Yes	Yes	Yes	Yes
CCS	Static	Yes	No	Yes	Yes

SNs are in GLIDING state. The state is switched to FALLING with probability given by $f(t)$, where $t = t_{drop}$. In FALLING state SN moves vertically with $speed = V_z$ and no horizontal movement takes place. SNs periodically broadcast a control message containing their mobility parameter m. SN on receiving the control message increments its counter n_f for every $m = 1$ and counter n_g for every $m = 0$ during T_h time interval. The total number of control messages n_d received by a SN is given by Eq. (4).

$$n_d = n_f + n_g \tag{4}$$

At the end of time interval T_h if n_d is found greater than the threshold, then the density of SNs is considered to be more than required. This is an indication for SNs to switch their state to GLIDING with probability p (as given in Eq. (5)) to enhance the process of dispersion.

$$p = \begin{cases} 1, & if \ \frac{n_d - N_d}{n_f} > 1 \\ \frac{n_d - N_d}{n_f}, & otherwise \end{cases} \tag{5}$$

$$N_d = \frac{r_c^2}{R^2} N \tag{6}$$

where N_d is the local density of neighboring SNs. If the time of the ride exceeds H/V_z then state of SN is switched to GROUND. Similar to FALLING state in GLIDING state SNs broadcast control message and increment their counters n_f, n_g and n_d based on m contained in control messages received from other SNs. At the end of time interval T_h, if n_d is found less than gliding threshold k_g then the density of SNs is considered to be less than required (i.e., If $n_d < k_g * N_d$). This is an indication for SNs to switch their state to FALLING with probability p to enhance the process of dispersion. If the time of the ride exceeds H/V_z then state of SN is switched to GROUND. GROUND state is a final state achieved after time interval H/V_z when SNs hit the ground. SNs change their mobility parameter $m = 0$ and continue to broadcast control message at time interval T_h.

UAD is an effective initiative for uniform deployment of static SNs over large candidate region using aerial vehicles, but the scheme ignored the effect of wind and terrain of candidate region; moreover, UAD suggested the use of motor driven propeller for horizontal gliding movement, which will consume large amount of energy.

4.2. Centrifugal Cannon based Sprinkler (CCS)

In [34] authors proposed, Centrifugal cannon based sprinkler (CCS) for scattering of SNs within a candidate region. The main objective of the model is to minimize the number of scans of deployment helicopter over the large-scale candidate region for a time efficient scattering. It is an electromechanical model is inspired from centrifugal sprinkler used in agriculture fields for spraying water to the crops. It works on the law of centrifugal energy, i.e., at specific RPM the centrifugal force exerted on the object depends on the distance at which it is held from the center (length of the cannon). It consists of an assembly of cannons (of variable lengths) one end of which is connected to a common junction point called Multi-path Intersection Point (MIP) (shown in Fig. 5). Hopper is used for dumping and holding the SNs before scattering, while the flow control knob regulates the rate of spreading of SNs.

CCS effectively reduces the number of scans required to scatter SNs within a candidate region, thereby drastically decreasing the time required for scattering, but with a slight decrease in coverage in comparison with point to point dropping scheme (PPD) which is not a feasible method for large-scale deployments.

Graph in Fig. 6 shows that UAD yields a slightly better performance in comparison with CCS due to involvement of additional hardware used to determine the density of SNs while dropping, but CCS is more suitable, cost effective and time efficient model for large-scale deployment due to its method of scattering. Comparison of random scattering schemes is shown in Table 1.

5. Random scattering + relocation

In these schemes of deployment, initially SNs are deployed by dropping from the flying machine (helicopter, airplane, etc.) over the candidate region, and low cost parachutes are preferably used to ensure safe landing of SNs. Base Station (BS) is mostly placed outside the candidate region and is considered

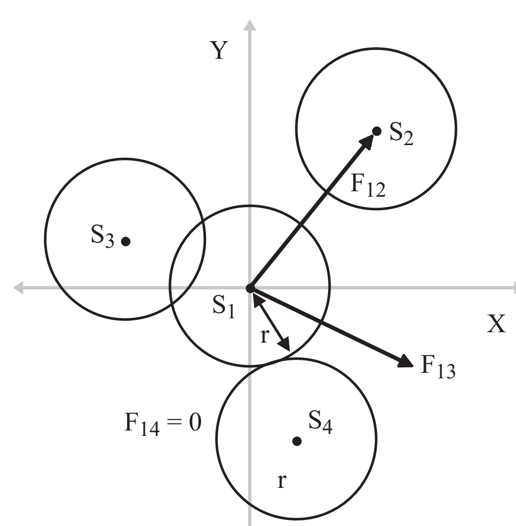

Figure 7 Force exerted on MSNs (redrawn from [35]).

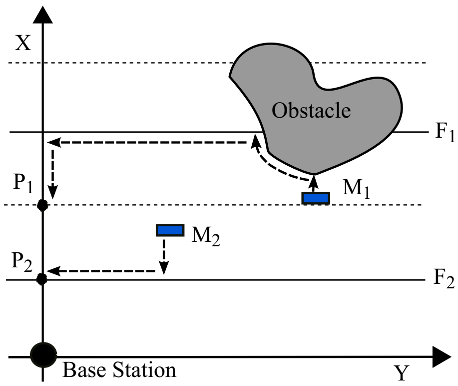

Figure 8 Movement of MSNs toward BS to gain connectivity (redrawn from [37]).

to have sufficient resources in terms of energy. Every SN is considered to have limited communication range (r_c) and r_s. SNs are mounted on a mobile device to change their position during the relocation phase. Deployment can be homogeneous (consisting of SNs with same configuration and capability) or heterogeneous (consisting of SNs with different configurations and capabilities).

5.1. Virtual force based method

Virtual Force Method (VFM) is a cluster based approach [35], in which randomly spread MSNs form a cluster based on their random physical locations. One of the MSNs is elected as Cluster Head (CH) which is responsible for managing other MSNs. VFM is evolved from PFM [32] and method of packing equal circles in a square [36]. Each of the deployed SNs exerts a force on other SNs. The force exerted by SNs can be attractive or repulsive, depending on the distance of the Nodes. If two MSNs are very close to each other (distance being less than the predefined threshold) then, they exert a repulsive force on each other to increase the coverage. In contrast to this, if two MSNs are far apart from each other (distance being more than predefined threshold) then they exert an attractive force on each other in order to come close enough to uniformly spread in the candidate region and to maintain connectivity, while the obstacles exert force of repulsion $\vec{F}_{Ri}$ and force of attraction $\vec{F}_{Ai}$ is exerted by regions with low density of MSNs (see Fig. 7).

The attraction and repulsion consume large amount of time and energy. These are not performed physically in contrast, they are logically performed by the CHs and final destination is decided for each MSN. VFM uses MSNs to minimize the network traffic by transmitting information in binary form (yes or no) to their CHs on detection of an event. Detailed information is only transmitted on demand. If any target MSN (S_t) is detected by MSNs in any cluster, they inform their detection to the CH using binary signals (yes or no), based on these signals, CH determines the candidate MSNs (that can participate in positioning S_t). CH then asks candidate MSNs to get detailed information about S_t.

VFM effectively reduced MSN movements by performing various logical movements at CHs before final movements of MSNs, but connectivity with BS is not guaranteed.

5.2. Connectivity preserved virtual force

Connectivity Preserved Virtual Force method (CPVF) [37] ensures the connectivity of every randomly spread MSNs in the candidate region. This is achieved by moving all the MSNs in a straight line toward the BS to get connected. While moving in a straight line, MSNs uses BUG2 algorithm [38] and lazy movement strategy to deal with obstacles and to minimize their movement, respectively. After getting connected to BS, another phase starts to expand the coverage of network while maintaining connectivity. This phase uses VFM [35].

BUG2: BUG2 algorithm uses "Right Hand rule" for handling obstacle by moving around it with the right hand touching its boundary until a line of reference is found, and line of reference is followed again to reach the destination point.

Lazy movement: CPVF uses Lazy Movement strategy in order to minimize the MSN movement. MSNs regularly check for nearest neighboring MSN moving ahead (MSN closer to the destination) toward the destination, on finding such neighbor, MSN stops for a certain interval in a hope that the neighboring MSN will get connected to the destination node to form a communication path. This process is repeated until all the MSNs are connected to the destination.

CPVF guarantees network connectivity along with reduced MSN movements by incorporating lazy movement strategy, but the scheme lacks scalability.

5.3. FLOOR based scheme

FLOOR based scheme is an enhanced form of Connectivity Preserved Virtual Force Method (CPVF) [37]. In this scheme the candidate region is logically divided into several Floor Lines separated by a distance $d = 2 * r_s$ as shown in Fig. 8. Similar to CPVF, FLOOR based scheme uses BUG2 algorithm and Lazy Movement strategy to deal with obstacles and to minimize MSN movement, respectively. After the random dispersion of MSNs in candidate region, they start moving to their nearest Floor lines. As in Fig. 8 M_1 and M_2 move toward Floor-Lines F_1 and F_2, respectively, after reaching Floor-Lines, M_1 and M_2 follow their Floor-Lines to reach y-axis, and then y-axis is followed by M_1 and M_2 to move

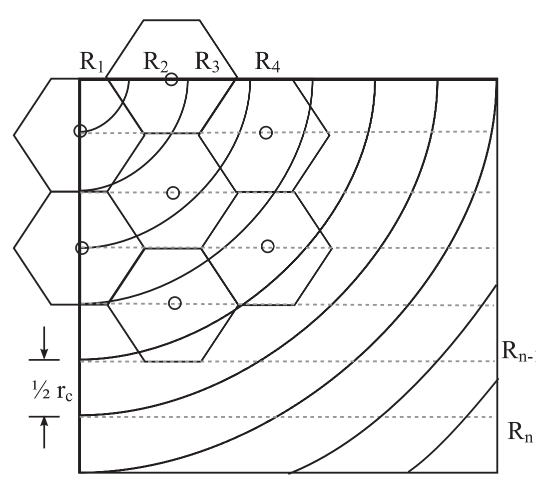

Figure 9 Logical division of a candidate region (redrawn from [40]).

toward origin, although they stop at points P_1 and P_2 as they get connected to the BS while following this path.

MSNs intimate BS after getting connected, in response to which BS sends the IDs of all their ancestors to them. This phase aims at determining, which MSNs can be moved to expand the coverage without splitting the network. For becoming movable, MSNs attempt to search new parents for their children MSNs, so that the children remain connected. They also determine the area covered by them at current location by checking the locations of their neighbors, if the area covered is less than certain threshold value, only then they become movable.

MSN with least value of x-coordinate on particular floor is elected as Floor-Head which is responsible for keeping information about all the MSNs on that floor. MSNs also check for the uncovered locations in their vicinity so that a movable MSN can be called to cover the region, and this is computed by checking the position of neighboring MSNs on the same floor and position of neighboring MSNs on adjacent floors, obtained from their Floor-Heads.

After all the movable MSNs are identified, they are moved to expand the coverage. Non-movable MSNs search for the uncovered regions in their locality and then determine the point at which the movable MSN can be placed to effectively cover that region.

Uncovered Patches left between r_s of SNs on adjacent floor lines inhibit the model from achieving 100% coverage but it minimizes the MSN movements.

5.4. Push-pull based distributed deployment scheme (PPDD)

In PPDD [39] authors presented a distributed scheme for homogeneous deployment of MSNs over a candidate region. It divides the entire region into hexagonal tiles by placing a MSN at the center of each tile and the process is called tiling. Tiling is initiated by several MSNs at arbitrary geographical locations at random time intervals by placing its neighboring MSNs at the center of adjacent tiles considering its own position as an initial point. It requires no prior information about the candidate region. The entire scheme is divided into 4 basic activities namely, Snap, Push, Pull, and Tiling merge.

Snap: The process is ignited by various MSNs at various geographical locations at random time intervals considering their location as the center of the first tile. The boundaries of the tiled sub-region are expanded by snapping the neighboring MSNs to the adjacent hexagons and the same process is repeated by newly snapped MSNs until the boundaries of candidate region are reached or tiling headed by another MSN is encountered.

Push: After the completion of snapping activity, there are still few unplaced MSNs (slaves) within the hexagon owned by the snapped MSNs. Push operation is performed by shifting such slaves from the region of high density to low density. Shifting of slaves take place, if the number of slaves in the adjacent hexagon is less than its own and cycles are avoided by making shift operation conditional (i.e., shifting of slaves only takes place to the hexagon owned by MSN with lower Id value).

Pull: Even after the completion of push activity, some holes persist. Pull activity is initiated by the snapped MSNs, if any hole is found in their vicinity. Snapped MSNs trigger a message specifying their demand for a slave.

Tiling merge: Process of tiling is simultaneously carried out by several master MSNs at arbitrary geographical locations which creates a disparity in the arrangement when tiles of one sub-region come in contact with other. The problem is solved rearranging the MSNs according to the oldest sub-region.

Although the process of tiling starts concurrently at various geographical locations within a candidate region, the model ends with the process of re-tiling during tiling-merge activity to adjust according to the oldest tiled sub-region, which is dependent on the size of the candidate region and leaves the model nonscalable.

5.5. Distributed Deployment Scheme (DDS)

Authors in [40] proposed a distributed deployment scheme (DDS) for homogeneous distribution of MSNs within the candidate region. DDS employs BS to logically divide the entire candidate region into several concentric layers centered at it and each layer is separated by half of r_c as shown in Fig. 9.

BS then computes all the desired locations for placement of randomly spread MSNs. Desired locations are computed by dividing the candidate region into regular hexagons (with side = r_s) and center of these hexagons constitutes desired locations. The relation between r_s and r_c is given by Eq. (7)

$$r_c = r_s * \sqrt{3} \tag{7}$$

BS invites randomly spread MSNs layer after another (starting from inside) to occupy the desired locations, thereby getting connected. If any layer doesn't contain MSNs then BS waits for certain time t ($t \geqslant$ maximum time taken by MSN in current layer to move up to last occupied layer) and invites the MSNs in the next layer to move toward connected nodes to get connected.

The process is repeated until all the nodes are placed on desired locations. DDS shows the multi-path connectivity, with minimum overlap and achieves 100% coverage with limited MSN movement, but the scheme is not scalable as MSNs are deployed in linear fashion (layer after another) due to which Deployment time increases with the area. Moreover MSNs have mobility restricted to plain surfaces which leave the system incompetent for real time scenarios.

5.6. SEEDS: Scalable Energy Efficient Deployment Scheme for homogeneous wireless sensor networks

Another scalable deployment scheme was proposed by Munish et al. [41]. It was designed to maximize the area covered by the minimum number of sensor nodes and attain complete connectivity with the minimum relocation of SNs. It is similar to DDS [40] as both of these use same relation between communication and sensing range (given by Eq. (7)) and method for determining desired locations for placement of SNs by dividing the candidate region into regular hexagons, is also same. Moreover, both the models are designed to achieve blanket coverage over large open-area candidate region where random scattering of SNs from the air is done in the initial phase of deployment. However, it is different from DDS in terms of claimed scalability and distributed algorithm used by it to concurrently move MSNs to appropriate desired locations within a candidate region. It also consists of an obstacle handing algorithm as its integral part. Base Station broadcasts the complete list of precomputed Desired Locations (DLs) to randomly scattered MSNs, which is sorted by them based on their Euclidean distance from each DL. MSNs then start moving toward each DL in the order specified by the sorted list until unoccupied DL is achieved. Placed MSNs broadcast STOP message after regular intervals in order to stop MSNs arriving to that DL. MSNs thus stopped, sort their remaining list and start moving again in the same pattern. Obstacles are handled using Bug2 algorithm [38] explained in Section 6**.**

Shortcoming of this model is that the size of the DL list increases with the area of candidate region, which further increases the size of broadcast packet and computation overhead on MSNs as they repeatedly have to sort this list based on their current location. Similar to DDL this method is also not scalable.

5.7. Distributed Self Spreading Algorithm for mobile wireless sensor network (DSSA)

DSSA is a SN deployment scheme for distributing MSNs uniformly within a candidate region by repeatedly relocating them to achieve desired density of MSN throughout [42]. DSSA is motivated from the balance of molecules within certain compound in terms of their density and space between them. Every MSN independently makes decisions regarding the magnitude and direction of movement. Decisions regarding the movement of MSNs are made on the basis of the combined force exerted by neighboring MSNs and the difference between local density D_l and desired density D_x levels. D_x for given area A of a candidate region with N number of MSN is given by Eq. (2).

$$D_x = \frac{N * 2 * \pi}{A} \tag{8}$$

$$F_n^{i,j} = \frac{D_l}{(D_x)^2}(r_c - |p_n^i - p_n^j|)\frac{p_n^j - p_n^i}{|p_n^j - p_n^i|} \tag{9}$$

Force exerted on MSN i by neighboring MSN j is represented by $f_n^{i,j}$ in Eq. (5). Where, p_n^i gives the position of ith MSN at time step n. The resultant force F acting on i due to all its neighboring MSNs is given by combining all the forces acting on i. MSN is considered to be stopped in following conditions:

1. If MSN does not exhibit movement of distance, greater than d_{min} (minimum distance for movement) for time T (due to insufficient fuel or failure of MSN).

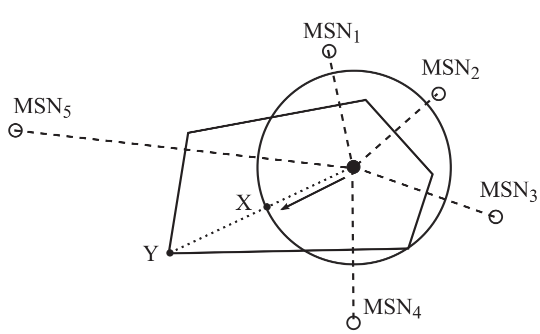

Figure 10 MSN movement in VOR (redrawn from [44]).

2. If count of oscillations O_c (back and forth movement of MSN on the same path) by MSN exceeds certain oscillating limit O_{lim}.

DSSA effectively minimized MSNs movements by controlling oscillations, but connectivity with BS is not guaranteed.

5.8. Fault Revoking and Homogeneous Distribution (FRHD)

Authors in [43] proposed a framework for fault revoking and homogeneous distribution of randomly deployed SNs in WSNs. This scheme employs heterogeneous SNs (i.e., MSNs as well as Static Sensor Nodes (SSN)). MSNs have the capability to pick and drop SSNs in order to relocate them whenever required.

SSNs perform the basic task of sensing surroundings and transmitting the data gathered to the CH while MSNs serve the purpose of post deployment configuration by relocating SSNs to suitable locations and CH thereafter. Extra MSNs called Fault Revoking Sensor Nodes (FSNs) are kept in the candidate region to serve the network at the time of occurrence of fault by replacing the dead nodes. BS logically divides the candidate region into equal sized subdivisions (preferably square in shape) and generates a subdivision list containing the starting coordinates of subdivisions. It broadcasts the subdivision list in the candidate region. MSNs in the candidate region compare their location with the coordinates in a subdivision list to identify the subdivision to which they belong and send ‘‘hello’’ packet to the BS to claim the ownership of subdivision. If MSN is the first one to claim, then it is elected as the owner of that region else it is granted the ownership of nearest unoccupied subdivision and instructed to move to that subdivision.

After the association of MSNs with subdivisions MSNs check the availability of sufficient number n_{avg} of SSNs in their subdivision. If SSNs available in any subdivision are less than n_{avg}, then MSNs in depriving subdivision communicate with neighboring MSNs to fetch extra SSNs in their territory to the common boundary from where it can pick SSN and place it in the appropriate location. If neighboring subdivisions don't have extra SSNs then FSNs are requested to fetch extra SSNs from corresponding subdivisions to deprived subdivisions thus performing homogeneous distribution.

FRHD attempts to achieve uniform SN distribution by ensuring sufficient number of SNs within a subdivision, but the position of SNs within the subdivision is not specified; moreover, FRHD uses MSNs for relocation of SNs which seems to be unreal for uneven terrains.

5.9. Vector Based Algorithm (VEC)

Authors in [44] proposed three algorithms for uniform dispersion of MSNs within a candidate region. All the algorithms use Voroni's graphs to detect holes in the candidate region. Coverage over the region is expanded either by pushing force exerted by regions having dense MSNs or by pulling force exerted by the regions having sparse MSNs. Vector Based Algorithm (VEC) is a push based approach. It assumes that there exists a force between two MSNs and between MSNs and boundary of candidate region that resembles the repulsive force that exists between two similar charged particles. Average distance

(d_{avg}) between adjacent MSNs is computed initially, which is considered as standard. Repulsive force is exerted by MSNs if the distance between them is less than d_{avg}. Unnecessary movements of MSNs are controlled by computing coverage benefit of a proposed move. Proposed move is rejected if the resultant position fails to achieve increased coverage. Coverage at any point is computed by the intersection of Voroni's polygon and sensing region of particular MSN. If the target position computed is too far then point at distance $\frac{1}{2}$ or $\frac{3}{4}$ of total distance is considered as the target position.

5.10. Voroni Based Algorithm (VOR)

Voroni Based Algorithm (VOR) [44] works on the pull driven approach in which MSN tends to fill holes in their Voroni's polygon by moving toward its farthest vertex as shown in Fig. 10. Excessive MSN movements are controlled by restricting their displacement to r_c–r_s and Voroni's polygon is redrawn while moving as new neighboring MSNs are discovered. Oscillations are controlled by keeping record of the previous move and avoiding immediate backward movement.

5.11. Minimax

Minimax algorithm [44] works similar to VOR to cover holes in its locality by moving toward the farthest vertex with a condition that closer vertices do not become furthest while moving toward target location and distance between MSN and farthest vertex is the minimum possible distance. The final point, thus computed for placing MSN is called minimax point. All of three algorithms enhance coverage by displacing MSNs to more appropriate locations which consume the major part of total energy.

5.12. Centroid Based Movement Assisted sensor deployment schemes in wireless sensor networks (CBMA)

Authors in [45] presented centroid based and dual centroid based schemes for homogeneous distribution of SNs within a candidate region. Both are iterative schemes which compute the centroid of the Voroni's polygon thus formed by MSNs to relocate them to it. Relocation of MSNs is preceded by evaluating the benefit of movement (in terms of enhancement in the coverage after relocation). Method for computation of centroid (C_x, C_y) of Voroni's polygon with vertices (x_i, y_i) is given by Eqs. (10) and (11).

$$C_x = \frac{1}{6a}\sum_{i=0}^{n-1}(x_i + x_{i+1})(x_i y_{i+1} - x_{i+1} y_i) \tag{10}$$

$$C_y = \frac{1}{6a}\sum_{i=0}^{n-1}(y_i + y_{i+1})(x_i y_{i+1} - x_{i+1} y_i) \tag{11}$$

$$a = \frac{1}{2}\sum_{i=0}^{n-1} x_i y_{i+1} - x_{i+1} y_i \tag{12}$$

Centroid scheme: It is executed in several phases. At the starting of every phase, each MSN computes its local Voroni's polygon using location information of neighboring MSNs. New centroid C_1 is computed by each MSN, if its local polygon is not covered completely. Relocation to C_1 is finalized on the basis of the benefit of the movement.

Dual centroid scheme: It is an expansion of centroid scheme. In addition to C_1, another centroid C_2 is computed for the polygon formed by the neighbors surrounding particular MSN and position for relocation is determined based on Eq. (13).

$$G = \alpha C_1 + (1 - \alpha) C_2 \ (\alpha \in (0, 1)) \tag{13}$$

5.13. Scan-Based Movement-Assisted Sensor Deployment Methods (SMART)

Authors in [46,47] presented a post deployment reconfiguration scheme for uniform distribution of MSNs randomly spread in the candidate region. SMART is motivated from load balancing techniques used in distributed systems [48,49]. It divides the whole candidate region into sub-regions (forming a 2-D grid of squares) of size i^2 as shown in Fig. 11, and then a sequence of scan operations is performed to equally distribute MSNs within each sub-region. Scanning operation is basically divided into horizontal and vertical scans which further consist of forward and backward scans (say, from left to right, and then from right to left) for every row and column. Forward sweep computes the total number of MSNs while backward sweep equally distributes MSNs in sub-regions in traversed row or column. Another variant makes use of a global average to initiate CHs of overcrowded sub-regions to instruct extra MSNs to move along the rows or columns, passing through adjacent sub-regions, while CHs of starving sub-regions monitor and interrupt passing MSNs to fill the holes of their sub-regions.

This scheme of 2-D scan works conditionally when all the sub-regions are populated with at least one MSN that can serve as CH to carry forward the scanning procedure. An additional procedure of seeding is included to supply starving sub-regions with an MSN to meet minimum requirement for algorithm to proceed.

SMART attempts to globally distribute MSNs uniformly within the candidate region, but the position of MSNs within sub-regions is not well defined.

5.14. Sensor deployment approach using glowworm swarm optimization algorithm (GSO)

GSO [50] is motivated from the behavior of glowworms, i.e., they emit a substance called luciferin which radiates energy in the form of light and its intensity varies with distance. Every glowworm is attracted toward its neighbor having the highest intensity of glow and starts following its movements thus forming clusters. In this scheme converse of glowworm's behavior is explored to uniformly distribute MSNs within the candidate region. MSN is considered as a glowworm with modified behavior that it will be attracted toward the neighboring glowworm having intensity less than its own. Luminance form particular SN can only be detected if the distance between them is less than r_c.

Every MSN is aware of its location coordinates, and based on this it calculates its distance from neighboring MSNs. This computed distance is used by MSN to determine its own

2	3	4	3	2	4
3	23	4	8	57	19
5	13	3	31	2	6
4	8	3	2	3	4
2	6	20	4	22	78
7	8	11	11	5	6

(a)

3	3	3	3	3	3
19	19	19	19	19	19
10	10	10	10	10	10
4	4	4	4	4	4
22	22	22	22	22	22
8	8	8	8	8	8

(b)

11	11	11	11	11	11
11	11	11	11	11	11
11	11	11	11	11	11
11	11	11	11	11	11
11	11	11	11	11	11
11	11	11	11	11	11

(c)

Figure 11 SMART (redrawn from [46]).

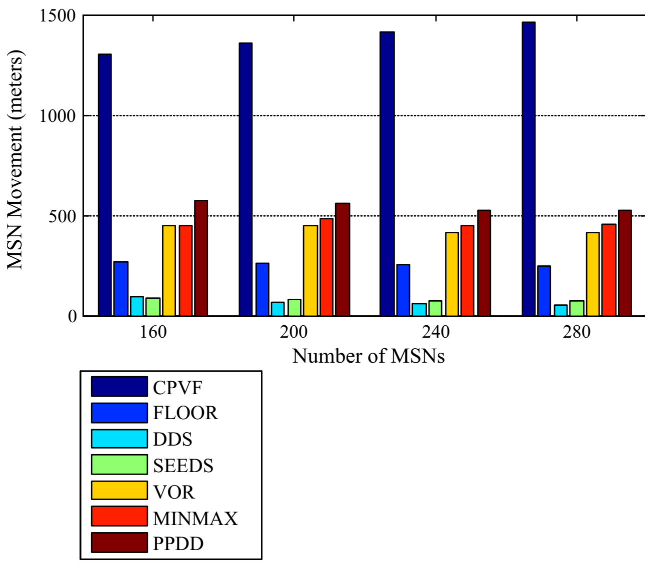

Figure 12 Comparative analysis of random scattering + relocation based schemes.

luciferin intensity. Based on the intensity of luciferin, MSN computes the probability of movement toward each neighboring MSN and selects the one with highest probability. MSN then move toward the selected MSN until the distance between them is greater than $\sqrt{3}r_s$. This process is repeated to uniformly spread the MSNs within the candidate region.

This scheme is suited only when MSNs have significantly high r_c in order to determine the intensity of luciferin of neighboring MSNs.

5.15. Analysis of random scattering + relocation based deployment schemes

According to Table 2, most of the schemes make use of mobile robots (i.e., MSNs) so as to relocate them after initial random-droppings from the air. Even though, various researchers have attempted to minimize MSN movements, it still consumes the major part of the energy. Comparative analysis of MSN movement required by various schemes is shown in Fig. 12. Moreover MSNs are more sophisticated devices which have limited mobility and accessibility for varied terrains.

As shown in Table 2, few schemes including CPVF, FLOOR, DDS, PPDD and SEEDS guarantee the connectivity of SNs with BS which enhances the network reliability, while other schemes simply focus on uniformly spreading SNs within the candidate region.

Scalability is important, as it generalizes the scheme for any size of candidate region and keeps it independent of other variables. Most of the schemes except DDS and SEEDS are scalable. Few schemes (i.e., PFM, VFM, CPVF, FLOOR, SEEDS and PPDD) included algorithms to deal with obstacles in candidate region, which is more realistic, while other schemes simply considered the candidate region to be plain surface without obstacles. Sophisticated obstacles of external environments (i.e., bushes, shrubs) are considered by none of

Table 2 Comparative analysis of random scattering + relocation based deployment schemes.

Scheme	Sensor type	Connectivity type	Connectivity guaranteed	Relocation model	Scalable	Obstacle resistant	Terrain independent
VFM [35]	Mobile	–	No	VFD	Yes	Yes	No
CPVF [37]	Mobile	Multi-path	Yes	VFD	Yes	Yes	No
FLOOR [37]	Mobile	Single-path	Yes	Hybrid	Yes	Yes	No
PPDD [39]	Mobile	Multi-path	Yes	Hybrid	Yes	Yes	No
DDS [40]	Mobile	Multi-path	Yes	PRP	No	No	No
SEEDS [41]	Mobile	Multi-path	Yes	PRP	No	Yes	No
DSSA [42]	Mobile	–	No	VFD	Yes	No	No
FRHD [43]	Mobile and static	–	–	–	Yes	No	No
VEC [44]	Mobile	–	No	VFD	Yes	No	No
VOR [44]	Mobile	–	No	VFD	Yes	No	No
MINIMAX [44]	Mobile	–	No	VFD	Yes	No	No
CBMA [45]	Mobile	–	–	VFD	Yes	–	No
SMART [46,47]	Mobile	–	No	–	Yes	No	No
GSO [50]	Mobile	–	No	–	Yes	No	No

the random scattering + relocation based schemes. Candidate regions are mostly the unreachable, hazardous environments with uneven terrain. Indulgence of ground MSNs makes the scheme more dependent on the terrain of a candidate region. However, random scattering schemes (i.e., UAD and CCS) are independent of the terrain of a candidate region.

Moreover, most of the schemes use aerial dropping method to randomly scatter SNs within a candidate region, but none of them took into account the impact of regional wind on the droppings.

6. Discussion

SNs are aerially dropped from helicopter moving at a certain altitude above, the candidate region; thus, each SN owns a potential energy, which is due to its high dropping altitude. This energy is converted into kinetic energy when SN is dropped from the helicopter, which causes an adverse effect on the SNs while landing. Various measures viz., use of parachute with each SN for a smooth landing, use of spongy cover over the SN to absorb shocks are taken into account to ensure the intact landing of SNs within the candidate region. This energy may be utilized to precisely place the falling SN on the desired locations (DLs). Bio-inspired deployment models can be designed by taking inspiration from flying patterns of birds, viz. Eagles, Vultures, which can precisely reach their prey on the ground (irrespective of the direction of atmospheric winds) without even flapping their wings.

Precise dropping of SNs on their DLs makes the model independent of the type of SNs (i.e., SSN or MSN) as no post-dropping relocation is required for their optimal placement. Since the SNs directly land on their DLs, the model is independent of terrain (i.e., marshy land, uneven land, sandy land) and resistant to obstacles (i.e., buildings, water bodies, shrubs).

7. Conclusion

Random scattering of SNs from the air is the most feasible method of deployment in vast and unreachable areas, but deployment from sky suffers various uncontrolled external factors such as wind, obstacles, and steep slopes may govern the random deployment and may lead to uneven distribution of SNs within the candidate region.

Winds are natural and can't be left unconsidered in aerial deployment of SNs. In aerial deployment SNs are mostly dropped with the help of small parachutes which may be drowned away by the winds to undesirable locations. Natural environments have excessive vegetation (in the form of bushes, shrubs, etc.) which may hinder the movements of MSNs in the candidate region so null or minimal movement of SN after dropping should be preferred. Existing deployment methods have not discussed such scenarios.

In this paper various schemes for deployment of MSNs have been studied and analyzed on various matrices. Existing methods of deployment are limited in their capabilities of real time implementations in hostile environments as most of external variables are underestimated and even not considered that may dynamically hamper the operation of any deployment scheme.

The comparative analysis depicts the improvements in deployment methods over years of research. As WSN with MSNs is expected to work in hostile and unpredictable environments with limited power and computational resources, there exists a great scope for researchers and robot designers to design algorithms and mechanisms to optimize the deployment while dealing with obstacles and uneven terrains of large scale candidate regions.

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