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Cost Modelling and Studies with Different Deployment Strategies for Wireless Multimedia Sensor Network Over Flat and Elevated Terrains

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Abstract Wireless multimedia sensor networks (WMSNs) is widely used for surveillance application. These multimedia (audio and video) nodes are distributed according to different deployment strategies in a multi-tier heterogeneous architecture environment. In this paper we have modelled the deployment cost of WMSN considering the sensor type (audio or video), sensor configuration such as remaining energy of battery, deployment point, and terrain characteristics for surveillance applications. Using our proposed cost models we have studied the effects of different deployment strategies of WMSN over flat and elevated terrains. Our cost models helps in minimizing the cost of deployment while maintaining Quality-of-Service i.e., the coverage and connectivity of the audio and video sensors separately. We have formulated an integer linear program and proposed a heuristic solution to minimize the placement costs subject to network coverage requirements using our first cost model. Our second cost model is used to propose a scheme that will ensure connectivity of the network. We have done simulations with three network deployment strategies, namely deterministic, random and hybrid and show that the hybrid deployment of sensor nodes yields a balance of performance and cost as compared to the other two. Our study provides guidelines for the network architect to select a particular deployment strategy under performance and cost requirements.

Keywords Wireless multimedia sensor network (WMSN) · Minimum deployment cost (MDC) · Integer linear program (ILP) · Approximation algorithm · Cost models · Connected target coverage

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1 Introduction

Wireless sensor networks (WSNs) have many important applications such as environment and health applications, structural monitoring, smart monitoring, and military target tracking and surveillance. A range of classes of sensors are available for such applications. These include temperature, pressure, acceleration, seismic, acoustic, radar, and camera sensors. WSNs are classified as terrestrial, underground, underwater, mobile, and multimedia sensor networks based on the environment in which it is deployed. Wireless multimedia sensor networks (WMSNs) have the ability to deal with multimedia data such as audio and video [1]. These networks are heterogeneous in nature, and are deployed to monitor public events, critical area including country borders. Multimedia systems widen the horizon of traditional video surveillance systems by enlarging, enhancing and providing multi-resolution views of the system, and are known as new generations of surveillance systems [2, 3].

WMSNs deployment may take several forms such as deterministic, random (e.g., by dropping or scattering from a point), or hybrid (combination of both schemes) to meet the desired design goals. Deterministic deployment is the preferred choice for known target locations, moderate network and user-friendly terrain. On other hand, random deployment is the preferred choice for critical area surveillance. The combination of various deployment schemes are used to improve the network performance, and node placement should follow high Quality-of-Service (QoS) parameters and low deployment cost. The sensor node deployment is homogeneous or heterogeneous depending on whether the nodes are of similar or of different types. Available deployment strategies can also be classified as pre-deployment and post-deployment strategies. The pre-deployment deals with QoS issues during the design phase and post-deployment deals with QoS after network deployment phase. Redeployment is a post-deployment scheme in which deployment of additional nodes leads to increased QoS requirements according to Wang and Ding [4]. In addition, mobility can be associated with sensors and it leads to movement-assisted deployment [5]. However, these deployments face various challenges that have been investigated by many researchers over several years. Younis and Akkaya [6] report the state of the research on node placement, and its effects on WSN performance.

The optimal usage and deployment cost for sensors used in surveillance application is an interesting problem. According to Leoncini et al. [7], the deployment policy should minimize the number of nodes and meet the QoS requirements. The minimization of nodes under coverage requirements have been investigated by many researchers [7–9]. Minimization of active multimedia sensors with required coverage is also reported by many researchers [10, 11]. In addition to coverage, connectivity is also considered during optimal video sensor placement [12]. Wang et al. in [13] investigates the temporal coverage of rotatable and directional sensors for surveillance applications. Node optimization is also studied under various environments, like, obstacle-prone environment by Chang et al. [14], and layered architecture by Pandey et al. [15]. Studies indicate that the use of multi-tier architecture over single tier leads to lower the energy consumption, lower monetary cost and leads to an effective management of the network resources [16, 17]. The node placement problem is formulated under QoS constraints and is solved using heuristic and Integer linear programming (ILP) approaches by various researchers in [9, 18].

Lin et al. [19] asserts that there are costs associated with sensor deployments. There are two types of costs: *fixed* and *variable*. The fixed cost is the procurement cost of the sensor node in terms of economic units. The sensor cost can also be measured by various parameters such as sensor type, configuration and energy level. The variable cost is associated with sensor deployment. Moreover, the ratio of fixed and variable cost varies due to pricing issues, terrain, and deployment point [20]. Rekleitis et al. [21] presents the robotic path-planning with various cost functions for planetary terrain. This cost function represents the cost of travelling from current position to the specified location in three-dimensional (3-D) space. The cost function depends upon various parameters such as distance between current and final destination, slope and roughness of the terrain. The work most close to ours is that of [19] and [20] where the deployment problem is modelled as an iterative sensor deployment strategy. In [19] the variable number of camera sensors to be deployed in each round is computed with the help of an adaptive strategy. The authors in [20] proposes *on-demand* deployment scheme in which further deployment visits are scheduled only on demand. The second *proactive* strategy plans for future node failures and considers different cost ratios in [20]. However our work deals with three different one-time deployment strategies for heterogeneous multimedia sensors in a multi-tier architecture environment. Moreover, our cost models consider sensor type, terrain conditions and other real factors for the surveillance environment. In addition to coverage, connectivity is also taken into account while dealing with deployment cost modelling.

In our work, we consider the minimization of network deployment cost under connected coverage constraints with surveillance requirements. This is also known as minimum deployment cost (MDC) problem. We have developed two cost models CM_1 and CM_2. The cost model CM_1 works for the coverage plane, whereas CM_2 works for the connectivity plane respectively. The deployment is formulated as a heterogeneous WMSN placement problem utilizing our first cost model (CM_1). CM_1 takes into account the characteristics of a sensor and deployment point, and includes labour and administrative costs similar to the work of Kouakou et al. [22]. The placement problem is solved exactly by an ILP formulation in a medium scale and approximately by greedy approximation algorithm. We have not considered the placement problem for a very large scale network which has been kept as a future work. Finally, the connected network is proposed using our second cost model (CM_2). Our second cost model considers distance among the nodes and energy level of the nodes for setting up a connected network. Both the cost models are necessary in sequence to obtain the desired QoS and optimal deployment. The main contributions of this paper are summarized as follows:

1 Our first cost model considers the sensor type, deployment point, terrain characteristics such as slope and roughness which is reasonable for the surveillance application, whereas our second cost model takes distance and battery level of the sensors into account.
2 A probabilistic sensing model characterises audio sensor's real performance in terms of target coverage. The visual sensors are highly directional in nature and follows Boolean sensing model.
3 The deterministic, random and hybrid deployment strategies are selected for suitable scenarios. The terrain selected for surveillance application is a flat and elevated surface, which represents a real world model where sensors and targets can be placed only at deployable portions.
4 MDC problem is formulated as an optimization problem and solved using ILP and greedy approximation algorithm under various scenarios subject to coverage

constraints. The connected coverage is proposed using shortest path algorithm.

This paper is organized as follows: Problem statement and basic terminology is presented in Sect. 2. Section 3 defines the characteristics of wireless multimedia sensor, and also discusses the issue of audio and visual sensor coverage. This is followed by deployment terrain and cost function details in Sect. 4. Section 5 proposes the deployment cost optimization approach and performance evaluations are presented in Sect. 6. Section 7 presents the conclusion and future scope of work.

2 Problem Formulations and Terminology

Here we first define the basic notations used in our work and then provide the problem of minimizing the WMSN deployment cost.

2.1 Notations and Assumptions

Table 1 shows the notations and their meaning as used in this paper. The notations are explained in subsequent sections as and when they are used. The terms video sensor and visual sensor are used interchangeably in this paper.

To formulate the problem, we make the following assumptions:

1 WMSN is represented as a graph based model G. A graph G consists of V(G) and E(G), where V(G) is the set of sensors, and E(G) is an edge set. An edge occurs if two sensors are placed in each other's communication range (R_c).
2 A graph is k-connected if and only if every separating set has a size of at-least k. The connectivity is represented by $\kappa''(G) = k$ for all k-connected sensors.
3 The target is covered with some probability function if it lies in the sensing range (r_s) of the sensor. The uncovered targets are ignored in our work. In case, a target e^t is sensed by at-least m nodes, it is m-covered target, and written as $\kappa'(e^t) = m$.
4 All the sensors in WMSN are connected to the sink via sensor nodes. In case, the network is not connected extra nodes can be added to maintain network connectivity.

2.2 Network Architecture

We assume a network architecture where multimedia sensor nodes are deployed over a surface which is partly flat and partly elevated. The multimedia sensor nodes are a mix of audio and video sensors. A node can either be an audio or a video sensor but not both. The set of audio and video sensors have cardinalities Ψ and φ respectively. These sensors can be placed in *deterministic*, *random*, or in a *hybrid* pattern. If the sensors are placed deterministically over a given set of control points, it results in deterministic deployment. Each of the control point p is chosen from a deployable set ($p \in \Omega_d$). In case of inaccessible terrains, the sensors are placed randomly. A combination of random and deterministic deployment is used in a hybrid deployment scheme. In this type of deployment a part of the total number of nodes are randomly deployed over a given

Table 1 Notations used in this paper

Ω: Surveillance area
Ω_d: Deployable area, $\Omega_d \subseteq \Omega$
p: Deployment point
θ: Slope of the terrain
κ : Roughness factor
R_c: Communication range
r_s : Sensing range
Ψ: Available number of audio sensors
φ: Available number of video sensors
T: Number of targets
N: Total number of multimedia nodes, $N = \Psi + \varphi$
a^i: ith audio sensor, $1 \leq i \leq \Psi$
v^i: ith video sensor, $1 \leq i \leq \varphi$
e^t: tth target, $1 \leq t \leq T$
A: Set of audio sensors, $A = \{a^1, a^2, \ldots, a^\Psi\}$
V: Set of video sensors, $V = \{v^1, v^2, \ldots, v^\varphi\}$
S: Set of sensors available for deployment over coverage plane
$S = \{s_1, s_2, \ldots, s_s\}$, s_i is ith sensor
$S = A$ for audio deployment, $S = V$ for video deployment
S': Set of sensors available for deployment over connectivity plane
E: Set of targets, $E = \{e^1, e^2, \ldots, e^T\}$
χ_{th}(i): ith node threshold battery
χ_t(i): ith node battery at time t
χ_{max}(i): ith node maximum battery
$0 < \chi_{th}(i) \leq \chi_t(i) \leq \chi_{\max}(i), \quad \forall i \in A, V$
κ''(G): Connectivity of graph G
$\kappa'(e^t)$: Coverage of the e^t target, $e^t \in E$
CM_1: First cost model
CM_2: Second cost model
$f_c(i)$: Fixed cost of the ith sensor
f_{cmax}: Maximum fixed cost among sensors, $f_{c\max} = \max(f_c(i)), \quad \forall i \in A, V$
$f(p, \theta, \kappa)$: Variable cost function
w_1: Weights assigned to the *fixed* cost
w_2: Weights assigned to the *variable* cost
N_D: Number of sensors distributed randomly from a site
F_D: Flip distance

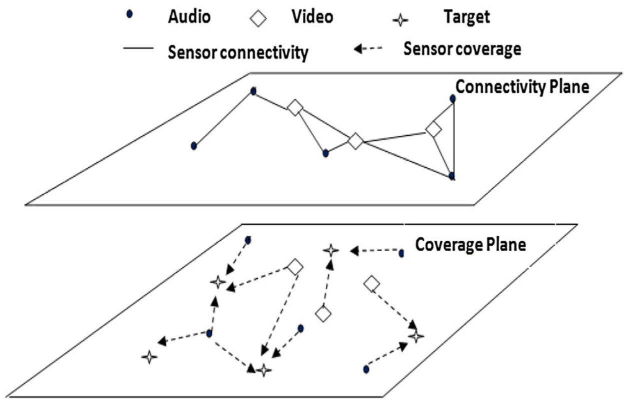


Fig. 1 Network architecture

terrain. The remaining nodes are then placed deterministically over a given set of control points. The network architecture is a multi-tier heterogeneous environment where deployed sensors preserve coverage and connectivity in different planes as shown in Fig. 1.

2.3 Problem Definition

The MDC problem can be defined as follows: Given a set of multimedia sensors A and V, a set of target points E, deployment strategy and cost model over a surveillance region Ω, find an assignment of sensor points with MDC such that overall target coverage and network connectivity is m and $\kappa''(G)$ respectively.

Two important QoS parameters, namely, target coverage and network connectivity (Fig. 1) are maintained in the MDC problem. The cost model CM_1 works for the coverage plane, whereas CM_2 works for the connectivity plane. The deployment of each sensor s_i at point p is associated with a positive cost function and is given by CM_1. The nodes are placed using optimization technique (Sect. 5) for deterministic strategy. In case of random strategy nodes are deployed from a central common point. The deployed nodes from the coverage plane are the candidates for the connectivity plane. CM_2 identifies the cost efficient edges for a connected network. The connected network in G is the shortest path from one vertex to the base station in a weighted graph (G).

Central to our approach is the cost modelling which can be used in different network settings under budget constraints. One of the goals of our work is to minimize the overall network deployment cost in terms of number of sensors, administrative cost, and energy consumption of the network. Our proposed strategy can be considered by network designer as part of the feasibility study during network design phase. Depending upon the terrain characteristics and geographical effects on pricing the ratio of sensor procurement cost to field trip cost varies significantly. We associate weights with sensor procurement cost and field trip costs. These weights can be adjusted by the network designer under various topographical conditions.

We also provide three deployment strategies which can be used in various application settings. Of the three deployment strategies, the choice of a particular strategy may be made based on terrain specifications, budget, and sensor characteristics. For accessible fields deterministic deployment is appropriate. In case of inaccessible terrains few deployment sites are identified and group of sensors are randomly spread from these sites. Thus visit to number of deployment sites significantly reduces as compared to deterministic and hybrid schemes. The hybrid scenario is a mix of random deployment and deterministic deployment scenario. Compared to a flat terrain an elevated terrain leads to a higher deployment cost. This is due to the fact that an increase in the slope of the terrain leads to an increase in deployment cost. Finally, the connectivity issue is raised by determining the residual energy and distance among sensors in the above deployment strategies. In case of deterministic scenario energy consumption among neighbouring nodes is predictable compared to random deployment.

3 Characteristics of WMSN

3.1 Multimedia Nodes

In this section we present the characteristics of wireless multimedia sensors. In this work, without loss of generality, we have considered only two types of multimedia nodes i.e., audio and video sensors (Fig. 1) wherein in both types we have included different categories. This heterogeneity is incorporated into the network so as to balance the cost and functionality of the network, improving the network scalability and exploiting the multiple levels of fidelity available in different nodes. The low capability node of a particular type of sensor can be used to replace the high-end nodes without degrading the coverage and deployment cost. Moreover, the deployment of single type nodes can be seen as a special case of a mixed deployment.

Several types of motes have recently become commercially available at nominal price for surveillance applications. The sensor motes are suitable as they are small and can easily be concealed for rapid deployment. It provides expansion for light, temperature, acoustic, magnetic and other sensor boards. For instance a moving person and a moving vehicle generate acoustic and magnetic signals, which can be measured by these motes. An acoustic sensor can measure the sound made by a person walking and wirelessly transmit this information back to the data fusion

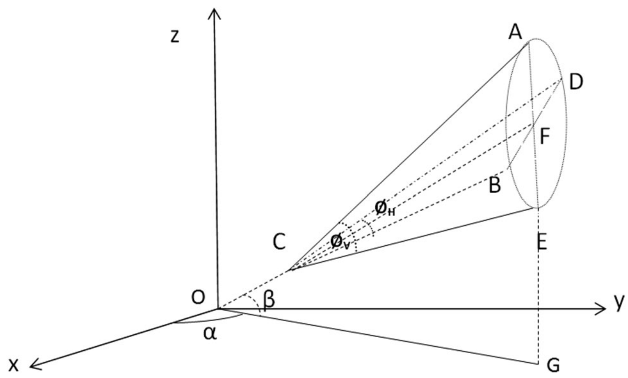


Fig. 2 The 3-D co-ordinates system and FOV of a camera. The camera is placed at C with coordinates as (c_x, c_y, c_z)

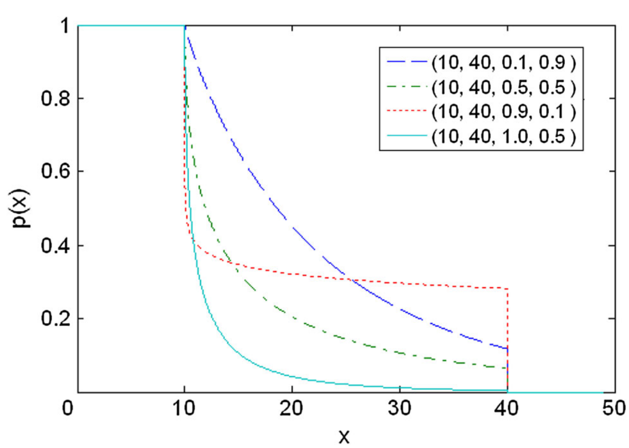


Fig. 3 Illustration of the probability detection $p(x)$ versus x

centre to perform tracking. Motes have also been used to develop sensor network based acoustic shooter localization in an urban environment [23].

We define the sensing and threshold range of our audio sensor based on well known Elfes function [24]. The threshold range (r_{th}) of an audio is defined as the range, where the probability of target detection is 1 (*one*). The sensing range (r_s) is defined as the range where sensor detects the target with some probability greater than zero. The sensor characteristic is determined by two sensor technology parameters λ and μ which are positive constants [24, 25]. Table 2 shows the parameter values for a typical audio sensor.

A video sensor is a directional sensor and differs from a traditional Omni-directional sensor because of their unique characteristics in 3-D space. The 3-D camera model is represented as a 5-tuple (C, P, Φ_H, Φ_V, d) [26, 27] where C is the camera sensor node with 3-D Cartesian coordinate as (c_x, c_y, c_z) and P is the camera's pose has an azimuth (α) and elevation angle (β) with respect to the 3-D Cartesian coordinate system. The values (α, β) are confined to a discrete set in Table 3 for simplicity. The parameter values of a typical visual sensor are summarized in Table 3. A camera's Angle of View (AOV) describes the angular extend of a given scene, and is also referred as Field of View (FOV) of a camera. The FOV can be measured diagonally, vertically and horizontally. The horizontal and vertical FOV refers to the maximum distance covered in the horizontal and vertical plane respectively. The horizontal and the vertical FOV of a camera are represented as Φ_H and Φ_V degrees respectively. The working direction is termed as the direction along the optical axis of the camera. The working distance (d) is the distance from sensor to object along the optical axis. These parameters are shown in Fig. 2 with respect to a 3-D Cartesian coordinate system.

Available video sensor nodes use a wide range of cameras having a very low-power with the camera nodes resolution ranging from low to high. The typical values for horizontal, vertical, and diagonal AoVs are given as 56°, 42°, and 70° respectively, according to Guvensan and Yavuz [28]. The sensing range of such available sensors is 132 m. The ratio of fixed (procurement) cost among audio and video sensor is of the order of (1:10), which is reasonable as visual sensors are complex and costly.

Table 2 Audio sensor parameters

Detection model: Elfes			
r_{th}: 10 m	r_s: 40 m	λ: 0.1	μ: 0.9

3.2 Coverage Models

It is important that the sensors are deployed in such a way that the primary QoS parameters are met. As mentioned in Sect. 3.1 the audio sensing model follow Elfes detection model. This model does not hold true for light and temperature [29], but is valid for acoustic sensors where sensing probability is a function of distance from the source. Mathematically it can be shown that following conditions hold for audio sensor.

$$p(x) = \begin{cases} 1 & \text{if } x \leq r_{th} \\ e^{-\lambda(x-r_{th})^{\mu}} & \text{if } r_{th} < x \leq r_s \\ 0 & \text{if } x > r_s \end{cases} \quad (1)$$

The target is detected with probability one, i.e. $p(x) = 1$ in case x is less than r_{th}, where x is the distance between the sensor and the target. In case x is greater than the sensing range (r_s) the detection probability is *zero*. However, the probability of detection is an exponential decaying function of x when $r_{th} < x < r_s$ as shown in Eq. (1). Figure 3 shows the probability of detection $p(x)$ versus the target distance x for different values of the parameters λ and μ. The sensing technology parameters of an audio node, a, can be expressed as a 4-tuple $a(r_{th}, r_s, \lambda, \mu)$. Different values of the

Table 3 Video sensor specifications

Detection model: binary		
d: 50 m	Φ_H : 56°	Φ_V: 42°
α:{0^0, 60^0, 120^0}; measured anticlockwise β:{0^0, 45^0}; measured clockwise		

parameters of a yield different results which represents the characteristics of various types of audio sensors. It is assumed that a target is detected by an audio sensor if the detection probability $p(x)$ is greater than a threshold value, *thres*.

A visual sensor has directivity associated with their sensing area and has a finite FOV. These nodes work only when there is no obstruction from the sensor to the target. The obstacle such as buildings or irregular terrain in the deployment environment leads to occlusion in video coverage.

The sensing range of visual sensor can be defined as volumetric coverage within the camera's FOV. We derive the video coverage based on the well established formulas in image processing. The camera model uses some basic transformations such as translation and rotation while deriving the mathematical formula where the angles are measured in clockwise direction in the 3-D Cartesian coordinate system (Fig. 2). Transforming the camera to the origin of the coordinate system we have:

$$x_1 = x - c_x, y_1 = y - c_y, z_1 = z - c_z \tag{2}$$

$$x_3 = \cos\beta \times (\cos\alpha \times x_1 + \sin\alpha \times y_1) + (\sin\beta \times z_1) \tag{3}$$

$$y_3 = -\sin\alpha \times x_1 + \cos\alpha \times y_1 \tag{4}$$

$$z_3 = -\sin\beta \times (\cos\alpha \times x_1 + \sin\alpha \times y_1) + (\cos\beta \times z_1) \tag{5}$$

The camera is rotated at an angle along z axis and along y axis. The maximum horizontal and vertical distances covered by the camera's FOV are given by L and M respectively. The target having coordinates (x_3, y_3, z_3) is said to be covered by visual sensor placed at (0, 0, 0) if the following Eqs. (6) to (8) are satisfied.

$$x_3 \le d \tag{6}$$

$$\left(-\frac{L}{2d}\right) \times x_3 \le y_3 \le \left(\frac{L}{2d}\right) \times x_3 \tag{7}$$

$$\left(-\frac{M}{2d}\right) \times x_3 \le z_3 \le \left(\frac{M}{2d}\right) \times x_3 \tag{8}$$

It is assumed that all targets in the sensor's FOV are covered with a probability 1 (one) where line of sight exists between the target and the sensor. Thus all such points satisfying the coverage criteria are sensed by the visual sensor. Mathematically it can be shown that following conditions hold for a video sensor:

$$p(x) = \begin{cases} 1 & \text{if } x \in FOV \\ 0 & \text{if } x \notin FOV \end{cases} \tag{9}$$

4 Cost Function Modelling

In this section we discuss the characteristics of the deployment plane along with the cost functions of the sensor nodes.

4.1 Deployment Plane

A terrain surface is represented as a grid where each point corresponds to an ordered pair (x, y, z) in 3-D Cartesian coordinate system. As given in Table 1 the surveillance area is represented as Ω. However, due to terrain characteristics, sensors can only be placed at some portions of Ω represented by Ω_d. The standard equation of a plane in 3-D system is given by:

$$A'x + B'y + C'z + D' = 0$$

$$z = -\left(\frac{A'}{C'}\right)x - \left(\frac{B'}{C'}\right)y - \left(\frac{D'}{C'}\right)$$

$$z = a'x + b'y + c' \tag{10}$$

$$z = c' \tag{11}$$

The elevated and the flat surfaces can now be represented by Eqs. (10) and (11) respectively. The sensor and targets are said to be placed at elevated or flat surface of the 3-D plane if the deployment point p ($p \in \Omega_d$) satisfies Eqs. (10) and (11) respectively. Slope and the roughness are the two important metrics in terrain analysis. Topographic roughness of a terrain can be specified in various ways such as standard deviation of the elevation, surface-area ratio and surface area. The ratio of surface area to plain-metric area is known as surface-area ratio and is a widely used landscape metric [30]. This ratio has a wide range of uses such as geomorphology and habitat assessment. In our work the surface-area ratio is represented as κ which we consider as the roughness factor.

4.2 Cost Function Modelling

The proposed cost models CM_1 and CM_2 along with the cost analysis for various deployment strategies are discussed in this section. As discussed in Sect. 1 the cost models CM_1 and CM_2 work for the coverage and the connectivity planes respectively.

CM_1 takes into account procurement cost ($f_c(i)$) and placement point (p) of the sensor and also the terrain characteristics such as slope (θ) and roughness (κ). These parameters are grouped into two parts, fixed and variable. The fixed-cost ($f_c(i)$) is defined as the cost of procurement

Table 4 CM_1 specifications

$f \propto \frac{E_d}{E_{d\max}}$, $E_d = \|q - p\|$, q and p are the position of the base station and sensor placement points respectively.
$p, q \in \Omega_d \cdot \|\frac{E_d}{E_{d\max}}\| \in [0, 1]$

$$E_{d\max} = \max(\|q - p\|), \quad \forall p \in \Omega_d \tag{12}$$

$f \propto (1 + \theta)$, $\theta = [0, \infty)$, one is added to avoid zero multiplication; β': plane elevation in degrees

$$\theta = 0; \quad \beta' = 0^\circ \tag{13}$$
$$= \tan(\beta'); \quad |0^\circ| < \beta' <= |75^\circ|$$
$$= \infty; \beta' > |75^\circ|$$

$f \propto \kappa, \quad \kappa = [1, \infty)$

$\kappa = \frac{\text{surface area}}{\text{plain-metric area}}$

$$\kappa = 1; \text{ is manageable terrain} \quad \kappa = \infty; \text{ unmanageable terrain} \tag{14}$$

$$f(p, \theta, \kappa) = \left(\frac{E_d}{E_{d\max}} \times (1 + \theta) \times \kappa\right) \tag{15}$$

$$CM_1 = w_1 \times \left(\frac{f_c(i)}{f_{c\max}}\right) + w_2 \times f(p, \theta, \kappa) \tag{16}$$

of the ith sensor and depends upon the type and characteristics of it. The variable cost is a function of (p, θ, κ) written as $f(p, \theta, \kappa)$ and is independent of the type of the sensor. We have assigned relative penalties to different grid cells based on distance, slope, and roughness of the terrain. Table 4 shows the CM_1 notations and their meaning as used in this paper.

Let us now refer to Eq. (15) where CM_1 varies directly with the distance from the base station which is positioned at a fixed point q. The distance can be measured based on Manhattan, Euclidean or any suitable distance measure. The increase in plane elevation (θ) results in the increase in the deployment cost. This is reasonable as elevated terrains are difficult to access and risky compared to flat terrain for surveillance applications. The ratio of fixed and variable cost also varies due to pricing issues and terrain environment [20]. In some scenarios procurement cost is given high weight factor and deployment cost is having low weight, whereas in other scenarios such as risky terrains it is vice versa. The weights (w_1 and w_2) are assigned to fixed and variable cost of the sensors respectively. The deployment cost as given by CM_1 is now represented by Eq. (16). This is an example of additive cost function where fixed cost represents the fixed cost of an audio or video sensor independent of its deployment point and f_{cmax} denotes the maximum possible cost of the sensor. The second term captures the variable cost which is an increasing function of the distance, slope and roughness for the terrain. Two cases for *variable* costs are explained in the subsequent discussion for flat and elevated terrains (Fig. 4).

CASE I: Flat terrain

$$f(p, \theta, \kappa) = \left(\frac{E_d}{E_{d\max}}\right) \times (1) \times (1)$$

$$\theta = 0$$

κ = surface area/plain-metric area = 1/1 = 1

CASE II: Terrain with 45° slope

$$f(p, \theta, \kappa) = \left(\frac{E_d}{E_{d\max}}\right) \times (2) \times \left(\sqrt{2}\right)$$

$$\theta = \tan\ 45 = 1$$

$$\kappa = \sqrt{2}$$

The deployed nodes from the coverage plane are the candidates for the connectivity plane. CM_2 identifies the cost efficient edges for a connected network and takes into account the Euclidean distance between two sensors and battery power of the destination sensor. Table 5 shows the CM_2 notations and their meaning as used in this paper.

CM_2 is explained graphically with the help of Fig. 5. Let us assume there is a source sensor p with s_1 and s_2 as two of its neighbours. Let the battery level of s_1 and s_2 be given by $\chi_t(s_1)$ and $\chi_t(s_2)$ respectively (Eq. 18). The Euclidean distance of s_1 and s_2 from p is represented along the x axis and the inverse of the battery power is represented along y axis. According to CM_2, the sensor selected for connected network as neighbour of p will have maximum area under the curve.

4.3 Cost Analysis for the Deployment Strategy

The deployment zone can be classified as accessible or inaccessible terrains. A good placement strategy maintains QoS parameters and leads to cost effective deployment. Of the three deployment strategies, the choice of a particular strategy may be made by the network planner based on terrain specifications, budget, sensor characteristics, and total deployment cost.

4.3.1 Cost Analysis for CM_1

For deterministic deployment strategy, CM_1 can be computed using Eq. (16). In such a scenario the coverage parameters can be predicted well in advance. However, in case of random deployment, CM_1 modifies into Eq. (21) where N_D is the number of sensors randomly distributed from a site. The equation can be given as follows:

$$CM_1 = w_1 \times \left(\frac{f_c(i)}{f_{c\max}}\right) + w_2 \times \left(\frac{1}{N_D}\right) \times f(p, \theta, \kappa) \tag{21}$$

A random deployment strategy identifies a limited number of deployment site(s) over a flat or elevated terrain. From each of these sites N_D sensors are randomly distributed with the help of a flip model. A flip model allows sensor to move only once to a new location bounded by a flip distance F_D [5]. The deployment cost reduces for each sensor in randomly deployed case as cost of carrying the sensors to a preferred deployment site is distributed among N_D

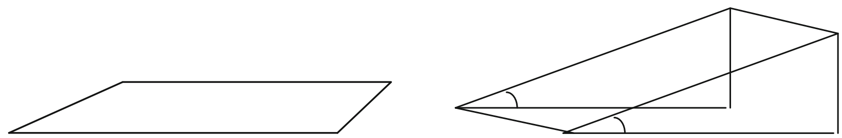


Fig. 4 Representation for a flat and an elevated terrain

Table 5 CM_2 specifications

$f \propto \|p - q\|$, p and q are the source and destination locations for sensors s_p and s_q over the connectivity plane respectively, $s_p, s_q \in S'$, $S' \subseteq S$	
$\|p - q\| = [0, R_c]$	(17)
$f \propto \frac{1}{\chi_t(q)}$, $\chi_t(q)$, is the residual battery power of the sensor q at time t	(18)
$\chi_t(q) \in (0, \chi_{\max}(q)]$, $\chi_{\max}(q)$, is the maximum battery power of the sensor q	
$f = \|p - q\| \times \frac{1}{\chi_t(q)}$	(19)
$CM_2 = \frac{\|p-q\|}{\chi_t(q)}$	(20)

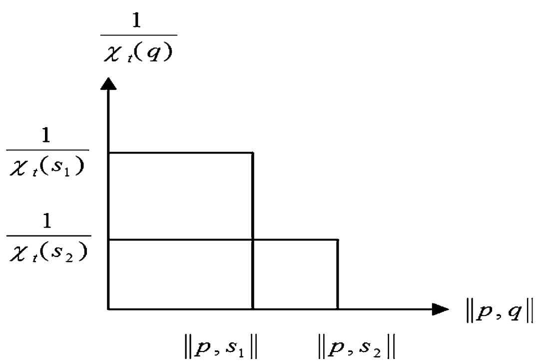


Fig. 5 Graphical representation of CM_2

sensors. However, in case of random deployment the coverage parameters prediction is a challenging task. Random and deterministic deployment follows in a sequence of steps for our hybrid deployment strategy. In this case a portion of sensors are randomly deployed using Eq. (21) followed by deterministic deployment with the help of Eq. (16).

4.3.2 Cost Analysis for CM_2

The deployed nodes in coverage plane form a connected network according to our second cost model CM_2. Here sensor p defines an edge weight with sensor q. Once the sensor is placed using any of the three deployment scenarios and CM_1, connected network is build using shortest path tree (SPT) and CM_2.

5 Deployment Cost Optimization

In this section we have formulated an ILP to minimize the deployment cost for a small sized network when the strategy is deterministic. We have also proposed a Greedy Approximation algorithm for medium to large size networks for the same type of strategy. We wish to cover the set of target points E given a sensor set S (S is the set of audio or video sensors) over deployment area (Ω_d). The objective is to achieve MDC using CM_1 subject to network coverage requirements. These deployed nodes S'($S' \subseteq S$)are then used to form a connected network with the help of SPT (Sect. 5.3).

5.1 Integer Linear Programming

We assume that there are Ψ audio and φ video control sites available for deployment. We also assume that an audio control site, a video control site and a target site with the subscript *i, j* and *k* respectively $(i, j, k \in \Omega_d)$ is present. Let c_{si} be the deployment cost associated with an audio sensor s at audio control site i $(s \in A, i \in \Omega_d)$.Let c_{sj} be the deployment cost associated with a video sensor s at video control site j $(s \in V, j \in \Omega_d)$. The deployment cost is computed using CM_1. In this work coverage by an audio and video control site (*i* and *j*) at a target site k is represented using variables ζ_{sik} and ζ_{sjk} respectively. The variables used in formulating an ILP are as follows:

x_{si} and x_{sj} are boolean variables for audio and video control sites *i* and *j* respectively.
$x_{si} = 1$ if an audio s is placed at control site i, otherwise 0.
$x_{sj} = 1$ if a video s is placed at control site j, otherwise 0.
$\zeta_{sik} = 1$ if an audio sensor s at control site i covers target placed at k, 0 otherwise.
$\zeta_{sjk} = 1$ if a video sensor s at control site j covers target placed at k, 0 otherwise.

The target at k is covered by a sensor placed at control site according to coverage model (refer Sect. 3.2). The objective function for the problem of MDC can now be stated as:

$$\text{Minimize}: \quad \sum_{s \in A} \sum_{i \in \Omega_d} c_{si} x_{si} + \sum_{s \in V} \sum_{j \in \Omega_d} c_{sj} x_{sj} \tag{22}$$

Subject to the following constraints:

$$\sum_{s\in A}\sum_{i\in\Omega_d}\zeta_{sik}x_{si} \geq \kappa'(k); \quad \forall k \in E \tag{23}$$

$$\sum_{s\in V}\sum_{j\in\Omega_d}\zeta_{sjk}x_{sj} \geq \kappa'(k); \quad \forall k \in E \tag{24}$$

$$\sum_{s\in A} x_{si} \leq 1; \quad \forall i \in \Omega_d \tag{25}$$

$$\sum_{s\in V} x_{sj} \leq 1; \quad \forall j \in \Omega_d \tag{26}$$

$$x_{si} \in \{1,0\}, \quad s \in A, \quad i \in \Omega_d \tag{27}$$

$$x_{sj} \in \{1,0\}, \quad s \in V, \quad j \in \Omega_d \tag{28}$$

The constraint in Eqs. (23) and (24) guarantees that all targets are covered by at-least m sensors ($\kappa'(k) = m$). The constraints in Eqs. (25) and (26) ensure that each control site has at-most one sensor. Equations (27) and (28) represent the Boolean values for audio and video control sites respectively. The types of variables are classified into two parts: audio and video. The increase in the value of Ω_d and N will increase the total number of variables. The variables required are of the order of $(N \times \Omega_d^2)$.

5.2 Greedy Approximation Algorithm

Here we propose a greedy heuristic algorithm that selects the local optimal choice. It expects that this strategy will lead to a global optimal solution. The heuristics approach requires coverage and cost matrix, and the same can be computed in advance thereby reducing the computational cost of the algorithm. The objective is to cover the set of target points (E) given sensor set S (S is the set of audio or video sensors) over deployment area (Ω_d) so as to achieve MDC using CM_1. The algorithm selects the sensor which have maximum ratio (σ) in each of its iteration. σ is defined as the ratio of CM_1 to number of covered targets. In the algorithm the targets covered by sensor s_i is given by: $\sum_{k\in E}\zeta_{s_i k}$

$$\sigma = \frac{CM_1}{\sum\limits_{k\in E}\zeta_{s_i k}}, \quad s_i \in S \tag{29}$$

The algorithm is given in Fig. 6 where maximum value of σ is selected in first iteration. This is followed by selecting the second maximum value (σ) compared to the first iteration. The process continues until coverage rate exceeds a user defined given threshold value. The algorithm can easily run in time polynomial in $|E|, |S|$ and the number of loop iterations is bounded by min($|E|$, $|S|$). In the next section result and analysis of two approaches are presented.

```
P←E
C←ϕ
while (P≠ϕ)
   temp←0; t1←0;
   for every s_i ∈ S do
         if (σ > temp) then
         temp← σ;  t1←i;
         end
   end
P ← P- (ζ_{s_t1,k} ∩ P)
C ← C ∪ s_t1
S ←S - s_t1
end
```

Fig. 6 Heuristic algorithm

5.3 Shortest Path Algorithm

A set of deployed sensors S' is obtained using CM_1 for the above mentioned deployment strategies. In case of deterministic deployment the cardinality of the set S' is less as compared to S ($S' \subseteq S$). However, in cased of random deployment the cardinality of S' is equal to the cardinality of S ($S' = S$). We construct the SPT in which edge weights are computed using CM_2. The SPT is constructed with base station as the source node and all nodes in set S′ as the destination nodes. This results in a coverage and connectivity preserved system.

6 Results and Analysis

From the discussions in the earlier sections we understand that the deployment cost varies with the given deployment strategies. To verify this, in our simulation, one parameter at a time is studied and its effect on the system is plotted keeping all other parameters constant as suggested in [31]. The simulation experiments are performed for three deployment scenarios using C program in Linux system equipped with a 3 GHz CPU and a 4 GB memory. CPLEX 9.1.0 has been used for implementation of the ILP model.

6.1 Simulation Using Greedy Approximation Algorithm

In our first set of experiment we use heuristic model according to the first cost model CM_1 for cost efficient deployment preserving coverage requirements. All the three deployment strategies are compared on our custom built simulator. In case of deterministic deployment the deployed nodes are a subset of the control points ($S' \subseteq S$).

However, in random deployment, we have $S' = S$. The number of deployment sites is limited to four in our simulation. Each of these sites carries an equal number of sensors and they are flipped from these four points using a flip distance F_D of 25 m. In case of hybrid deployment, half of the sensors are deployed using random strategy and rest half using deterministic deployment strategy.

The deployed nodes then form a connected network using SPT and CM_2. The effects of node density, slope, weights (w_1, w_2) and target density are studied. Network diameter and maximum distance from base station is used to evaluate the connected network. The simulation parameters used in this section are provided in Table 6.

Table 6 Simulation parameters used in the paper

Plane characteristics	
Deployment plane (m^2):	100 × 100
Elevation of plane (α°):	[0, 45]
Optimization	Heuristics
$w1$	{0.1, 0.5, 0.9}
$w2$	{0.1, 0.5, 0.9}
Connected network:	SPT
Node deployment	
Audio:	Deterministic/ random/hybrid
Video:	Deterministic/ random/hybrid
Targets:	Random
Audio:	[0, 100]
Video:	[0, 100]
Targets:	{25, 50, 75, 100}
Audio characteristics	
Fixed cost:	15
Normalized fixed cost:	0.1
λ:	0.9
μ:	0.1
r_{th}:	10 m
r_a:	40 m
thres:	0.9
R_c:	40 m
Detection model:	Elfes
Initial energy (J):	2
Video characteristics	
Fixed cost:	150
Normalized fixed cost:	1.0
Working distance:	50 m
Horizontal angle:	45°
Vertical angle:	42°
Azimuth angle:	{0°, 60°,120°}
Elevation angle (elevation angle is assumed to be aligned with the elevation of the plane):	{0°, 45°}
R_c:	40 m
Detection model:	Boolean
Initial energy (J):	20
Base station	
Location:	(0,0,0)
Initial energy (J):	50

6.1.1 *Effect of Node Density*

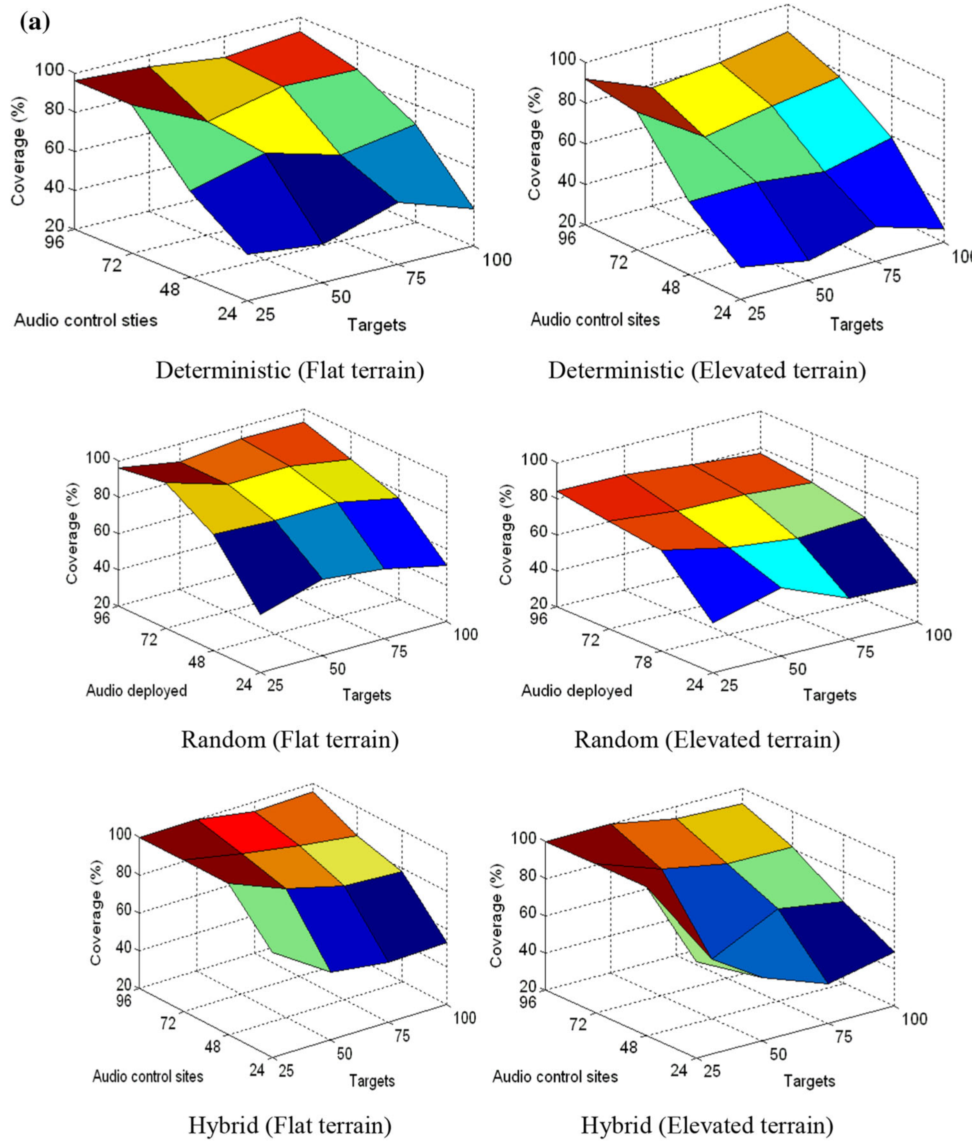
The network dimensions are kept fixed at 100 × 100 square metres, and the number of nodes is varied as 24, 48, 72 and 96 nodes (Fig. 7). In Fig. 7a we plot the coverage (%) versus no. of targets while the number of audio control points vary from 24 to 96 for deterministic, random and hybrid deployment. We give the plots for coverage percentage for number of targets versus audio control sites for the three deployment strategies over a flat and an elevated terrain. From these figures we observe that coverage for audio sensors is higher in case of hybrid strategy as compared to the deterministic. This is valid for both flat and elevated surfaces. In case of audio coverage, we find that hybrid deployment is the best strategy, whereas the deterministic deployment is the worst. In hybrid strategies 50 % of the sensors are first deployed randomly and the rest 50 % are deployed with the help of deterministic strategy. The two step deployment in hybrid scenario leads to a higher target coverage.

In Fig. 7b we plot the coverage (%) versus no. of targets while the no. of video control points vary from 24 to 96 for all the three types of deployments. The directional nature of visual sensors limits the coverage area even though a large number of randomly deployed sensors are used. In random deployment the QoS parameter increases non-uniformly over the uncovered regions. Even with the increase in sensor density some targets may remain uncovered in this type of deployment. From the figure we observe that percentage of targets covered in case of video sensors is more for hybrid strategy as compared to the deterministic one. This is valid for both flat and elevated surfaces.

6.1.2 *Effect of Slope*

In this subsection three deployment strategies are studied for variation of coverage deployment cost under the effect of slope as shown in Fig. 8. We find that in both types of terrains audio sensors yields less deployment cost compared to video sensors for all the three strategies. Moreover, the cost fluctuates with the weights and slope associated with the plane. Hybrid scenario offers a reasonable deployment cost compared to the other two. As can be seen from Fig. 8a deployment cost does not vary for randomly deployed sensors. This is due to the fact that the

Fig. 7 **a** Plot of coverage (%) versus number of targets versus audio control sites for deterministic, random and hybrid strategies over a flat and an elevated terrain. **b** Plot of coverage (%) versus number of targets versus video control sites for deterministic, random and hybrid strategies over a flat and an elevated terrain



variable component in Eq. (21) equally distributes the cost among the deployed sensors.

The plot of figures in Fig. 8b show that the deployment cost for video sensors is reasonable in case of hybrid strategy. This cost is high as compared to deterministic strategy but at the same time hybrid strategy provides better percentage of coverage Fig. 7b.

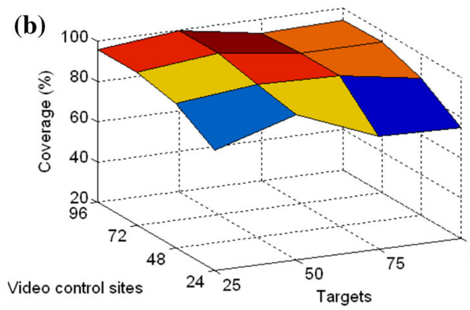
6.1.3 Effect of Weights

Here we study the variation in deployment cost with respect to the weights assigned to the fixed and variable components of cost model CM_1 (Eqs. 16 and 21). We observe that the deployment cost fluctuates with the weights w_1 and w_2 as can be seen in Fig. 9. In case of random deployment, we have $S' = S$, so deployment cost is independent of the target density. The increase in weight w_1 for the fixed component increases the deployment cost. Moreover, the variable component cost is distributed equally among N_D sensors. However, in deterministic and hybrid strategies shows the decrease in the deployment cost for audio deployment whereas in video deployment reverse is true. This is due to the fact that fixed component is significantly higher for video sensors as compared to audio sensors.

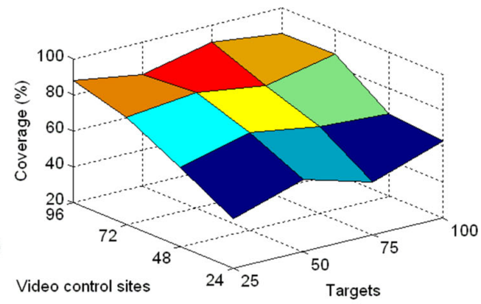
In Fig. 9 the plots for high node density and high target density are shown. It is seen that, in case of audio sensors the variable cost component is higher for deterministic and hybrid deployment strategies as compared to random strategy for a given number of nodes. The effect of reduction in w_2 reduces the variable component of deployment cost. The effect of increase in w_1 increases the fixed component of the deployment cost for all the three schemes.

Fig. 7 continued

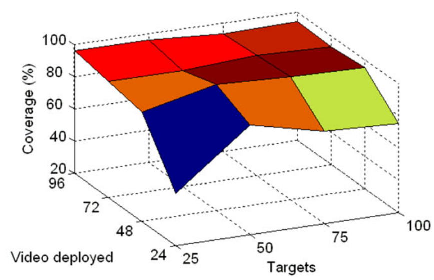
(b)



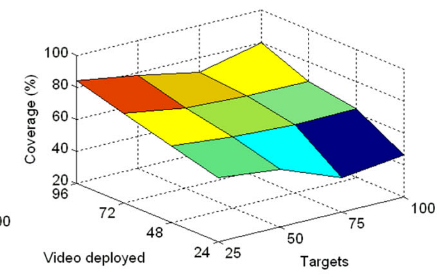
Deterministic (Flat terrain)



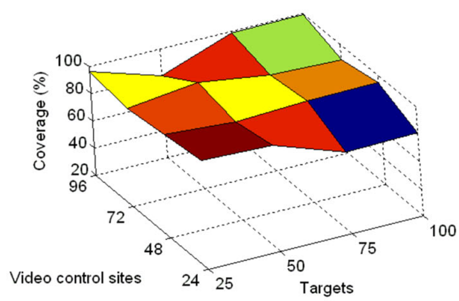
Deterministic (Elevated terrain)



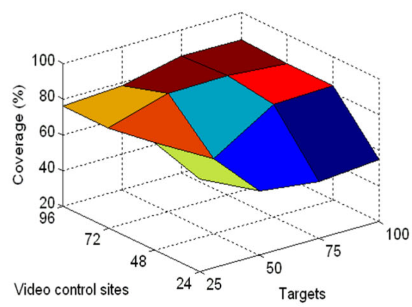
Random (Flat terrain)



Random (Elevated terrain)



Hybrid (Flat terrain)



Hybrid (Elevated terrain)

6.1.4 Effect of the Number of Targets

In this subsection the effect on the number of deployed nodes with an increase in the number of targets for various deployment strategies is studied. The deterministic deployment strategy leads to fewer sensors for covering a discrete set of targets. This is true for both audio and video sensors. On the other hand, random deployment places all the available sensors randomly over the terrain, whereas the hybrid scheme deploys a reasonable number of sensors.

Figure 10a, b plots the number of audio and video sensors deployed versus targets for low node density. In all of our observations the target points are varied from 25 to 100 for deterministic, random and hybrid deployment over a flat and an elevated terrain respectively. Random deployment is independent of terrain or type of sensors or target density and all the sensors are deployed. However in deterministic and hybrid schemes we observe that for a given number of targets the increase in node density leads to an increase in number of deployed nodes. This is due to the fact that an increase in node density leads to an increase in coverage which in turn increases the deployed sensors. Due to the directional nature of video the number of sensors does not increases linearly with an increase in the number of targets unlike audio in deterministic deployment.

6.1.5 Metrics for Connected Network

Network diameter and maximum distance from the base station is used to evaluate the connected network. The readings are taken for the following configurations: (24, 48, 72, and 96) sensors and (25, 50, 75 and 100) targets. The average of Network Diameter and average depth of connected network is computed for (25, 50, 75, and 100) targets (Fig. 11).

Network diameter and average depth is least for random deployment and large for hybrid strategy. This is due to the

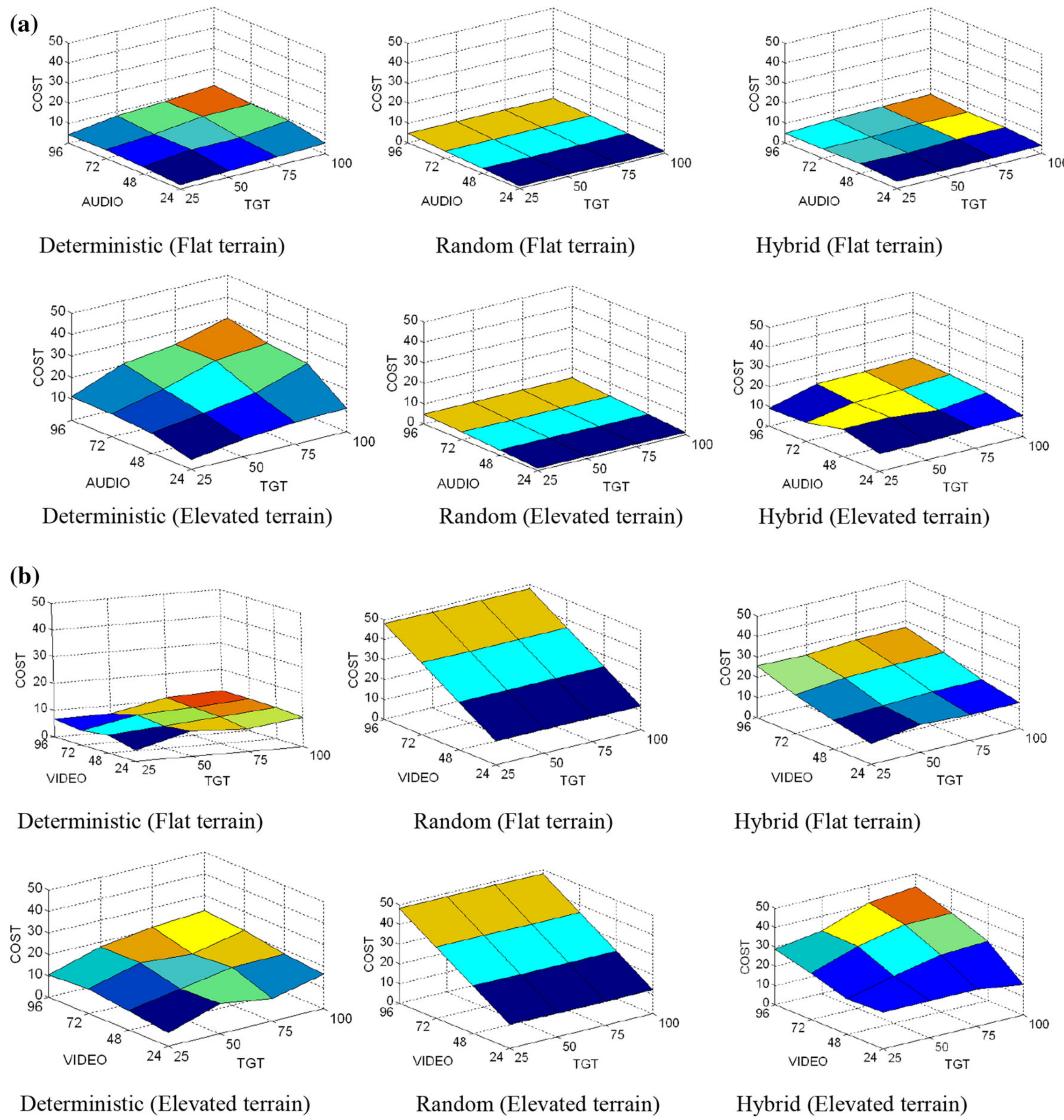
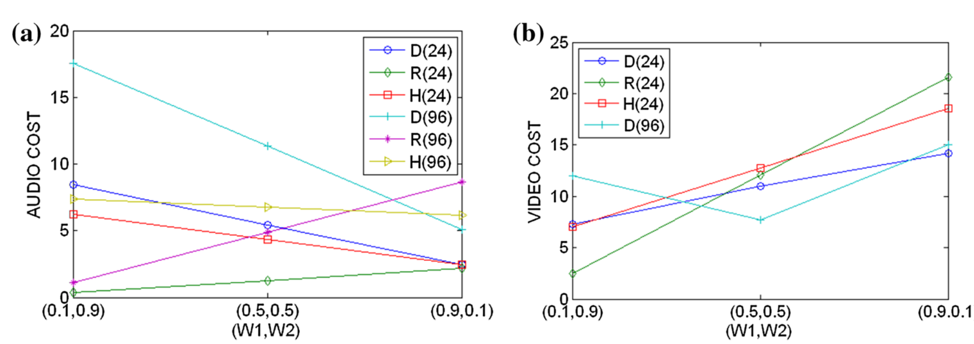


Fig. 8 **a** Plot of deployment cost versus number of targets versus audio control sites for deterministic, random and hybrid strategies over a flat and elevated terrain. **b** Plot of deployment cost versus number of targets versus video control sites for deterministic, random and hybrid strategies over a over a flat and elevated terrain

Fig. 9 The effect of weights for (**a**) audio deployment cost and (**b**) video deployment cost respectively



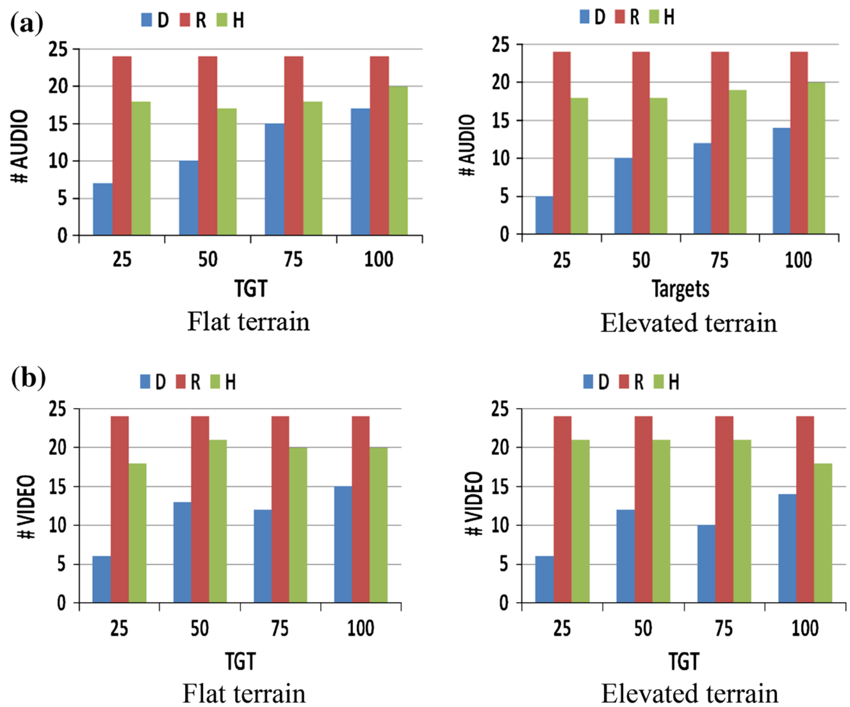


Fig. 10 **a** Number of audio sensors deployed for deterministic, random and hybrid (D, R, H) strategies for a given number of 24 audio sensors over a flat and elevated terrain. **b** Number of video sensors deployed for deterministic, random and hybrid (D, R, H) strategies for a given number of 24 video sensors over a flat and elevated terrain

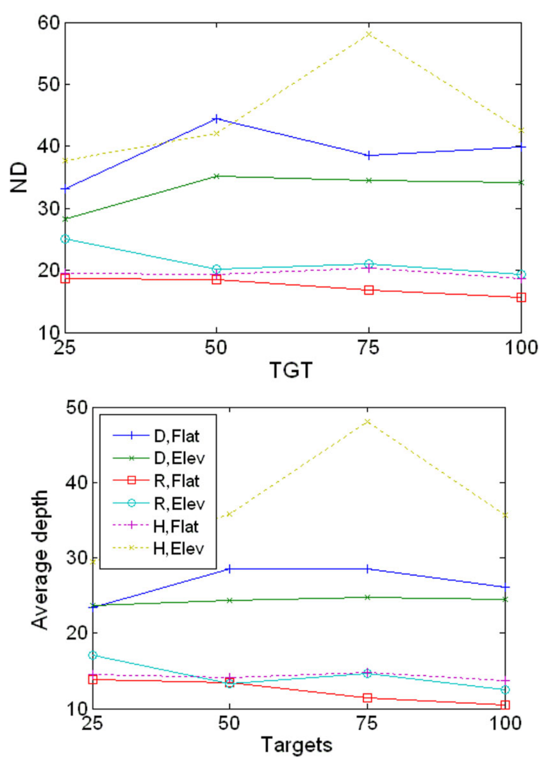


Fig. 11 Network diameter and maximum path length versus number of audio and video control sites for deterministic, random and hybrid deployment (D, R, H) over a flat and elevated terrains

fact that large number of randomly deployed nodes over a terrain increases the cardinality of $E(G)$. This increase in number of edges leads to an increase in the choice of a candidate edge for the formation of SPT.

6.2 ILP

In our second set of experiment we use ILP model according to CM_1 for cost efficient deployment subjected to coverage requirements. These deployed nodes forms connected network using SPT and CM_2. Table 6 presents the simulation parameters used to evaluate the ILP model over a flat terrain. The two components w_1 and w_2 are assigned the weights of 0.5 in this set of experiment. Moreover, this subsection compares the ILP and greedy approximation algorithm for deterministic deployment over a flat terrain.

As can be seen from Fig. 12a, b deployment cost for ILP is better as compared to the heuristic scheme due to greedy nature of the heuristic scheme. As can be observed from Fig. 13, ILP performance is better in terms of number of deployed nodes compared to greedy for deterministic deployment over flat surface. Greedy approach selects the local optimal choice in each of its iteration, whereas ILP selects the best outcome for a given scenario.

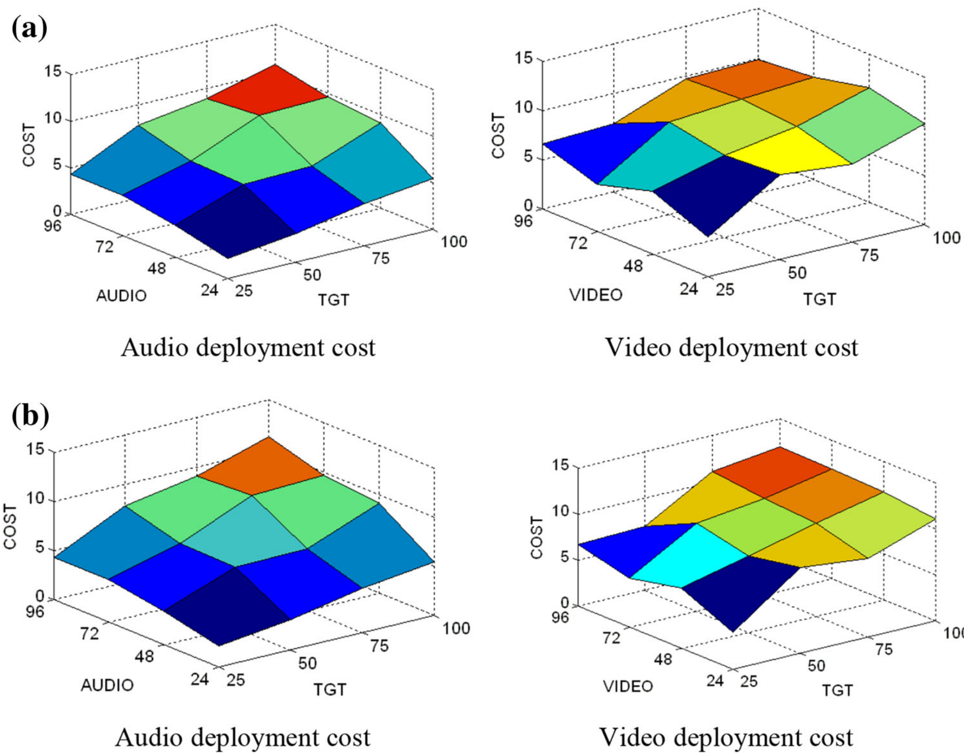


Fig. 12 **a** Plot of deployment cost versus number of targets versus control sites using ILP for deterministic strategy over a flat terrain. **b** Plot of deployment cost versus number of targets versus control sites using greedy approximation algorithm for deterministic strategy over a flat terrain

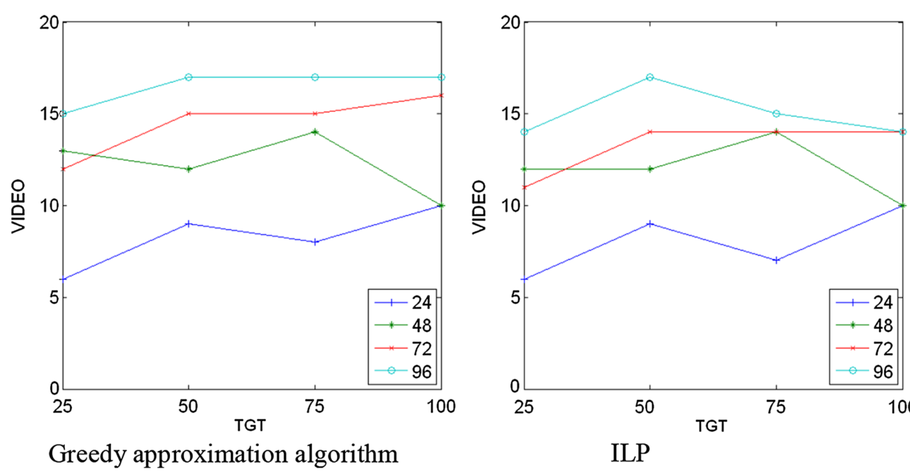


Fig. 13 Number of video deployed versus targets to be covered for various control sites in Greedy approximation and ILP

7 Conclusion

Node deployment is a fundamental issue in WMSNs. In this paper, we have addressed the MDC problem for surveillance application under deterministic, random, and hybrid deployment strategies over a flat and elevated terrain. The sensor deployment, which is formulated as an optimization problem is solved using ILP and a greedy approximation algorithm for medium size instances. We noticed that various deployment strategies yield different cost and network performances. Deployment cost fluctuates with change in fixed and variable component weights. The selection of these weights by network architect depends upon various factors such as terrain conditions, administrative cost, and procurement cost etc. Out of the three deployment strategies random deployment yields the minimum network diameter for a connected network. Simulation results show that the performance of greedy approximation algorithm is comparable to the ILP approach. The presented strategies in this paper can be used by a network architect for a given deployment budget and QoS requirements.

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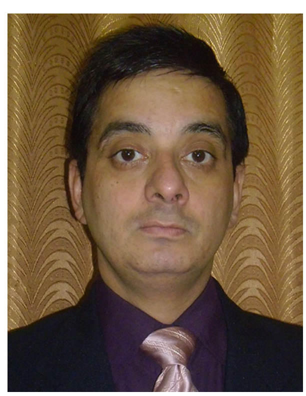
Author Biographies



Ravindara Bhatt received his B.E. degree in Electronics & Communication Engineering from H.N.B. Garhwal University, Uttranchal, India in 1996. He received Diploma in Advanced Computing from CDAC, and M.Tech. in Information Technology from Guru Gobind Singh Indraprastha University, Delhi, India. He is currently working towards the Ph.D. degree at Indian Institute of Technology, Kharagpur, India. He is a faculty member in the Department of Computer Science Engineering & Information Technology at Jaypee University of Information Technology, Waknaghat, Solan, India. His research interests include coverage, energy, and deployment problems in wireless multimedia sensor networks.

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