Paper

Heavy Gas Cloud Boundary Estimation and Tracking using Mobile Sensors

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Abstract—This paper addresses issues concerned with design and managing of monitoring systems comprised of mobile wireless sensing devices (MANETs). The authors focus on self-organizing, cooperative and coherent networks that maintain a continuous communication with a central operator and adopt to changes in an unknown environment to achieve a given goal. The attention is focused on the development of MANET for heavy gas clouds detection and its boundary estimating and tracking. Two strategies for constructing the MANET are described, in which sensors explore the region of interest to detect the gas cloud, create temporary network topology and finally, cover the cloud boundary, and track the moving cloud. The utility and efficiency of the proposed strategies has been justified through simulation experiments.

Keywords—deployment strategies, heavy gas cloud boundary tracking, MANET, mobile ad hoc network, mobility models, sensor networks.

1. Introduction

The management of emergency activities such as guiding people out of dangerous areas and coordinating rescue teams is characterized by uncertainty regarding both the source of danger and the availability of useful resources. Depending upon the scale and nature of the incident, people involved in a crisis may suffer from limited situational awareness. Situational awareness is a state of being aware of what is happening in an area of interest and understanding how information, events, and actions impact objectives. Inadequate situational awareness has been identified as a primary factor leading to human error in emergency situations, with grave consequences. Therefore, there is a huge demand for effective situational awareness systems that must gather data in a timely manner in order to create an evolving image of the emergency at hand, ultimately generating a holistic view of the emergency to be used by authoritative decision makers and emergency services. As emergency situations are chaotic in nature, data sources are usually dispersed throughout geographical areas due to dynamic nature of the disaster, situational awareness becomes a complex, distributed processing problem where innovative techniques need to be employed in order to effectively monitor and neutralize the threat.

In this paper the attention is focused on the effectively aiding with emergency situations caused by release of toxic gas. Extremely dangerous are heavy gas clouds formed by gas heavier than air (e.g. chlorine, nitrogen or sulfur dioxide). These clouds are usually created due to a natural phenomena (e.g. volcano eruption) or as a result of terrorist attack and military action. Furthermore, great amount of toxic substances are transported and stored by industries. Despite high safety standards gas tankers crashes, in which dangerous substance is released to the atmosphere, occur from time to time [1]–[3]. In general, in case of environmental disasters the extensive monitoring of the area of interest is necessary to manage the evacuation of people from a disaster zone, track the propagation of a given cloud, measure the level of contamination and finally, neutralize the cloud. As gas clouds are dispersed throughout geographical areas the innovative techniques need to be employed in order to effectively monitor and neutralize the disaster.

Mobile wireless ad hoc networks (MANETs) can significantly enhance the capability to investigate contaminated areas, in particular detect and track heavy gas clouds. In general, MANETs are comprised of wireless mobile devices (network nodes) that can dynamically and freely self-organize into temporary network topologies that can change rapidly and adopt to the changing environment [4]. Nodes communicate wirelessly and share the same radio channel. The devices located within their transmission range can communicate directly without the need for an established infrastructure and centralized administration. For communicating with devices located beyond the transmission range, a node needs to use intermediate nodes to relay messages hop by hop. Thus, in general, routes between mobile nodes may include multiple hops.

Advanced monitoring systems can be created by wireless sensors mounted on mobile platforms, i.e. unmanned vehicles, mobile robots or drones, and moved to desirable positions. Authors have developed two three-phase strategies for constructing MANETs, in which mobile devices, equipped with gas sensors and radio transceivers, explore the region of interest to detect a gas cloud, create preliminarily network topology, estimate a boundary of this cloud and track it maintaining the permanent communication with the central operator (base station). Such a sensing system can successfully support the management of emergency activities.

The paper is organized as follows. In Section 2 the problems and approaches to development of MANETs for dynamic processes sensing are investigated and discussed. In Section 3 a formal statement of a network and gas cloud propagation models is provided. All phases of creation of MANET for a gas cloud boundary estimation and tracking are discussed in Section 4. Two algorithms for such MANETs development are described in Sections 5 and 6. The results of performance evaluation of these algorithms are described and discussed in Section 7. The paper is concluded in Section 8.

2. Related Work

Large-scale heterogeneous wireless ad hoc networks are becoming a technological cornerstone for many important applications in today's society. These collections of autonomous and distributed nodes capable of sensing, communication, processing and self-organization are emerging as a new era of intelligent information-driven paradigms. Ad hoc networks are used in many applications such as surveillance systems, environment monitoring and unmanned space explorations. On the other hand, the deployment of these networks in industrial environments is generating tremendous streams of daily data and qualities which describe the operation, condition, performance and status of a wide range of equipment. This represents an additional large volume of data to explore, the need for more efficient and scalable data analysis methods and raises additional challenges on real-time stream data processing, distribution and storage. Furthermore, nodes of ad hoc networks are often small battery powered devices, which means their power source is limited. The network's throughput is also limited. Thus, various approaches to energy saving are considered, i.e. temporary deactivating selected nodes [5]–[8], decreasing number and size of transmitted messages [6], [7]. Moreover, poor deployment of sensor devices may lead in small coverage of a region of interest. The influence of poor placement of devices on network reliability, stability and availability is discussed in [9].

Another problem is the dynamic nature of sensing phenomena. Therefore, recently a lot of effort is put into movement-assisted deployment systems [10], [11]. Endowing sensors with mobility significantly expands capabilities of monitoring and tracking systems. Mobility allows to detect lacks of deployment objectives, improve coverage and communication connectivity even decreasing number of employed sensing devices. A large number of measurement targets can be handled with smaller number of migrating sensors. On the other side it is obvious that mobility implies an additional complexity layer. Paths on which vehicles carrying sensors can move to desired destination have to be calculated [12], [13], and internode communication has to be managed to imply connectivity among the working set of devices and a base station. Numerous strategies and approaches to global connectivity maintenance by network composed of autonomous mobile devices have been developed and described in the literature [14]–[16]. Presented algorithms enable to create network topologies with different characteristics (size, nodes' degree, etc.). Another problem is to discover redundant links in a sensing network that could be removed [17] or to indicate the region where the extra nodes should be supplied to restore the global connection [18], [19]. The description of numerous examples of monitoring systems built by static and mobile sensors can be found in literature, e.g. real time monitoring system for nuclear plant [20], mobile systems for environmental monitoring [21] and exploring unknown areas [22], [23]. In emergency situations mobile wireless devices can be used to establish new communication infrastructure for rescue teams [24], [25]. The system for firefighters that allows to conduct audio and video conference during rescue actions is described in [26]. The MANET-based communication infrastructure for telemedicine service is described in [27]. Kulla e*t al*. describe in [28] the application of MANET to maintain a permanent communication with a single robot that explores inside of a building in emergency scenario.

A significant attention in the recent years is focused on the application of mobile ad hoc networks for detecting and boundary tracking of phenomena clouds. Phenomena clouds are characterized by nondeterministic, dynamic variations of shapes, sizes, direction, and speed of motion along multiple directions. The phenomena cloud detection and tracking require more reliable techniques that can accurately adapt to the dynamics of a given phenomena, and should not limit to simple and well-defined shapes of clouds. In [5] a framework for environmental boundary estimation and tracking by considering the boundary as a hidden Markov model with separated observations collected from multiple sensing devices is presented. Based on the data collected from sensors and prior knowledge of the dynamic model of boundary evolvement the optimization problem is formulated. The boundary is estimated by solving this problem for prediction and current observation of a given phenomena.

The simpler but still challenging problem is to create mobile system for heavy gas clouds monitoring. In this paper authors focus on a heavy gas clouds boundary detection and tracking. Clouds created by heavy gas are very dangerous for human beings. They can move close to the ground for significant time at high level of gas concentration. In the significant number of works on a gas cloud, boundary detection is calculated based on estimated distribution of phenomena concentration [29]–[32]. It is assumed that concentration decreases smoothly to the boundary, which is inadequate for scenarios with heavy gas for few reasons. Firstly, the dynamics of a heavy gas cloud is very fast. Secondly, gas sensors can measure the gas concentration only at a given point. Furthermore, lower concentration can indicates a boundary or any obstacle in a working space. Therefore, the application of networks created by mobile sensing devices that can dynamically self-organize into coherent topologies is a viable solution for heavy gas clouds monitoring.

3. Problem Formulation and Sensing System Modeling

3.1. Model of Sensing MANET

Let us consider a network that comprises N autonomous mobile platforms (unmanned vehicles or mobile robots) D_i, $i = 1,\dots,N$ equipped with heavy gas detectors and radio transceivers that can create a sensing system in a two-dimensional workspace W with self-configuring capabilities. The objective is to deploy all devices to achieve the optimal sensing of boundaries of a given gas cloud to estimate a size of this cloud, and minimize the energy usage for carrying sensors. All devices can dynamically change their positions and the role in the network according to a current knowledge about the environment and the positions of all other devices in a network. Furthermore, it is assumed that all measurements can be transmitted to the central operator (base station) any time. Hence, the permanent communication with the base station has to be maintained.

In general, the design of self-organizing networks that can freely organize into temporary topologies is challenging problems. The development of applications relying on mobile devices and wireless communication protocols can be greatly simplified by the use of modeling and simulation tools. Therefore, authors have developed and investigated a simulation-based method to design and develop the MANET for heavy gas clouds detection, its boundary estimation and tracking. In presented approach the utility and efficiency of proposed sensing devices deployment strategies are evaluated through simulations.

In simulation-based designing the model of a system considered has to be created and implemented. Authors formulated a mathematical model of proposed network, modeling both radio signal proposed propagation and movement of all network nodes. In our model all network nodes are solid bodies with an arbitrary shape. In order to simplify the description of the system each network node is modeled by a polygon with its reference point $\mathbf{c}^i = [x^i, y^i]$, which is the location of the device (exactly its antena). The radio coverage region of each node is a disc of a radius r_t centered at the transmitter (exactly at the reference point $\mathbf{c}^i$ in case of D_i). The commonly used long-distance path loss model described in [33] was used for estimation of signal degradation with a given distance, and calculation of the internode distance d_{ij} in time t. In this research all sensing devices could be forced to move in advisable direction with the speed $v \in [v_{min}, v_{max}]$ while forming in time t a dynamic multi-hop network $\mathscr{G} = (\mathscr{V}, \mathscr{E})$ defined as follows:

$$\mathscr{V} = \{D_i, i = 1,\dots,N\}, \tag{1}$$

$$\mathscr{E} = \{(D_i, D_j), d_{ij} \le r_t, i, j = 1,\dots,N, i \neq j\}, \tag{2}$$

where (D_i, D_j) denotes a bidirectional link between a pair of nodes D_i and D_j that can be enabled or disabled in time due to node mobility, d_{ij} is the Euclidean distance between these nodes.

In presented study all devices D_i are autonomous agents that collaborating create a sensing network. Thus, the aim of each device is to reach the target point in a workspace that is defined by $\mathbf{c}_g^i = [x_g^i, y_g^i]$. To ensure permanent network connectivity motion trajectory calculated for each D_i depends on the positions of all other network devices D_j, $j = 1,\dots,N,\ j \neq i$ in the workspace W.

3.2. Model of Heavy Gas Cloud Propagation

To perform simulations with a sensing system for a heavy gas cloud monitoring it is necessary to model propagation of such cloud. The models of heavy gas dispersion are divided into several categories based on different criteria. Three main groups: empirical, research and engineering models are distinguished in [34]. Empirical models are developed based on environmental measurements and laboratory experiments. Mathematical models – formulated by sets of partial differential equations dependent on time and three space coordinates – provide complete and detailed description of the physical process of a heavy gas dispersion [34]. However, mathematical models require the estimation of numerous parameters and their application is usually limited to obstacle-free sensing area. The trade off are engineering models that are widely used in practical applications.

In the research, which results are presented in this paper, a simple engineering model described in [35] – the box model – was used to simulate heavy gas clouds propagation. The summary of this model is presented below. The heavy gas cloud is modeled as a uniform cylinder with dynamics described by a set of three linear ordinary differential equations:

$$\frac{d\bar{\mathbf{c}}_c}{dt} = v_c, \tag{3}$$

$$\frac{dr}{dt} = v_f, \tag{4}$$

$$\frac{dm_a}{dt} = \rho_{air}(\pi r^2)v_t + \rho_{air}(2\pi rh)v_e, \tag{5}$$

where $\bar{\mathbf{c}}_c = [x_c, y_c]$ denotes the position of the centre of a cloud, v_c, v_f, v_e, v_t denote following velocities: transport, gravitational and entrainment for edge and top of a cloud. r is the radius of a cloud, h its height and m_a is the entrained mass. ρ_{air} denotes the air density.

The Eq. (3) describes the spreading of the centre of a cloud, Eq. (4) the puff horizontal spreading influencing the cloud radius. Mass conservation is described by the formula (5).

The gravitational velocity v_f is calculated for a given standard gravity g. The height of a cloud h, cloud and air densities – ρ_c and ρ_{air} are calculated according to the following formula:

$$v_f = C_F \sqrt{\frac{g(\rho_c - \rho_{air})h}{\rho_{air}}}, \tag{6}$$

where C_F denotes the Froude number of the front (for dense gas models typically $C_F = 1.1$ [35]).
The relationship between the edge entrainment velocity v_e and the gravitational velocity is described as follows:

$$v_e = \alpha v_f, \tag{7}$$

where $\alpha \in [0.6, 0.9]$ (see [34]).
Finally, the entrainment velocity for top of a cloud can be calculated due to the equation

$$v_t = u_* \left(\frac{\kappa}{1 + \beta \frac{g(\rho_c + \rho_{air})h}{\rho_{air} u_*^2}} \right), \tag{8}$$

where $\kappa = 0,4$ denotes the von Karman constant [34], u_* the friction velocity [36], β the parameter (suggested value $\beta = 0.125$ [37]), ρ_c the current cloud density.
To calculate displacement of a cloud its density ρ_c and height h have to be determined. They depend on the concentration z of gas in a cloud. The value of z dynamically changes due to cloud mixing with an ambient air. It can be calculated due to the formula

$$z = \frac{\frac{m_0}{M}}{\frac{m_0}{M} + \frac{M_a}{M_{air}}}, \tag{9}$$

where m_0 is a mass of contaminant gas, M and M_{air} the molar weights of the gas and air respectively.

The relation between the gas concentration and its density notable influences a cloud dynamics. This relation is affected by many factors. In this research authors neglected chemical reactions and occurrence of any aerosol formations in the cloud. Mixing of gas with ambient air was the only source of density change – the density of gas was calculated according to the following formula

$$\rho_c = \rho_{air} \left(\frac{1 + z\frac{M - M_{air}}{M_{air}}}{1 + \frac{z\Delta H_0}{\left((1-z)M_{air} q_p^{air} + zMq_p\right) T_{air}}} \right), \tag{10}$$

where ΔH_0 denotes the enthalpy difference between the release material at the source and ambient conditions, q_p and q_p^{air} are specific heat capacities of gas and air respectively. T_{air} is the temperature of an ambient air.
Then, the height of a cloud h was computed

$$h = \frac{V}{\pi r^2}, \qquad V = \frac{m}{\rho_c}, \tag{11}$$

where V is the volume of a cloud.

The presented model was employed to simulate a gas dispersion in a flat area without obstacles. The Euler method was used to solve set of Eqs. (3)–(5). In general, this model is valid until the occurrence of one of two conditions [34]:

- the difference between the density of cloud and air is less than a small assumed value,
- the growth of a cloud radius in single step is small enough.

3.3. Model for Motion Trajectory Computing

The goal of mobility model is to describe the movement of all devices of a sensing network $\mathcal{G}$ in the workspace W, i.e., how their location, velocity, and acceleration change over time. The main problem addressed in many recent publications on MANETs is a high impact of the mobility of network devices on the overall network performance and connectivity. The mobility models should resemble the real life movements of all network nodes. Moreover, they should be appropriately reflected in simulations, which can be used to support design and management of a given network $\mathcal{G}$. A number of less and more detailed and accurate mobility models have been introduced, tested and implemented in various mobile networks. The survey and discussion of the taxonomies of mobility models and main directions to mobility modeling are provided in [12].
In the research presented in this paper the mobility model that resembles a collision-free movement of a group of mobile wireless devices is used. The model was adapted to coherent and cooperative network topologies construction. The algorithm for motion trajectories calculation and results of performance evaluation are described and discussed in [13]. This mobility model incorporates two techniques, the concept of an artificial potential and the concept of a particle-based mobility schemes. The artificial potential field can be viewed as a landscape where the mobile devices move from a high-value state to a low-value state. Thus, the artificial potential function, which value can be viewed as energy has to be defined for each network device. It is constructed as a sum of repulsive and attractive potentials. Its value depends on Euclidean distances between a given device and all other devices in a sensing network $\mathcal{G}$ and the distance to the target position and obstacles in the workspace W. Moreover, in the concept of a particle-based mobility each network device, is considered as a self-driven moving particle, and is characterized by a sum of forces, describing its desire to move to the target position, avoiding collisions with other devices and obstacles and maintaining continuous connectivity with the network head.
In a system formed by only one mobile device or set of non-cooperating devices moving in the workspace without obstacles authors can explicitly calculate the optimal position of each device (coordinates of its reference point $\mathbf{c}^i$) – the location close to its target destination $\mathbf{c}_g^i$. In presented case study the collaboration between network devices is required to explore a gas cloud, tackle its boundary and maintain communication with a network head. Therefore, the motion trajectory of each mobile device D_i de-

pends on the positions of all sensors located in its transmission radio range, i.e. neighboring nodes from the set $S_i = \{D_j : (D_i, D_j) \in \mathscr{E}, j = 1, \ldots, N, j \neq i\}$. In the adopted mobility model to calculate a new position of the device D_i the following optimization problem has to be solved

$$\min_{\mathbf{c}^i} \left[U^i = U^i_g + \sum_{D_j \in S_i, j \neq i} U^i_j = \right. \\ \left. = \varepsilon_g \left(\frac{\overline{d}^i_g}{d^i_g} - 1 \right)^2 + \sum_{D_j \in S_i, j \neq i} \varepsilon_j \left(\frac{\overline{d}^i_j}{d^i_j} - 1 \right)^2 \right]. \tag{12}$$

In the above formulation the performance measure – artificial potential function U^i consists of the potential U^i_g between D_i and its target g and a sum of potentials between D_i and D_j, $j \in S_i$. $\varepsilon_g \geq 0$ and $\varepsilon_j \geq 0$ denote weighting factors determining the importance of, respectively the goal g and the device D_j. d^i_g and d^i_j are real Euclidean distances, between $\mathbf{c}^i$ and respectively, $\mathbf{c}_g$ and $\mathbf{c}_j$ after a network transformation. $\overline{d}^i_g$ and $\overline{d}^i_j$ are the reference distances between $\mathbf{c}^i$ and respectively, $\mathbf{c}_g$ and $\mathbf{c}_j$ (calculated due to a current signal strength measurement). The final network topology depends on a target point location, and the established values of the reference distances $\overline{d}^i_g$ and $\overline{d}^i_j$ and weighting factors ε_g, ε_j in Eq. (12).

4. MANET for Gas Cloud Boundary Tracking – a Design Process

The investigated computing scheme for creating a MANET for a moving heavy gas cloud estimation of a cloud size and boundary consists of three phases:

1. Working space exploration.
2. Gas cloud detection.
3. Optimal deployment of sensing devices and a gas cloud boundary tracking.

In all listed phases network devices dynamically change their positions in W, thus at each timestep t the position of each network node in W is updated. The permanent connectivity with the central operator of the system is maintained.

Phase 1 – working space exploration. In the exploration phase the aim of the performance of a team of N mobile sensors D_i, $i = 1, \ldots, N$ that create a network $\mathscr{G}$, is to search for a heavy gas cloud in W. The device D_1 denotes the head H of this network. The network head is responsible for maintaining the connectivity with the base station using, e.g. a satellite connection. Moreover, it is assumed that all other devices D_i, $i = 2, \ldots, N$ enable the continuous wireless communication with H. Thus, for each pair of nodes (D_i, H) exists at least one path composed of links from $\mathscr{E}$ in time t. These devices move and follow the node H. The displacements of all network nodes are calculated according to the mobility model (12) for $U^i_g = U^i_j$, $j = i+1$, $i = 1, \ldots, N-1$ and $\overline{d}^i_j \leq r_t$. U^i_j denotes the potential between D_i and its successor.

Phase 2 – gas cloud detection. Let us assume that the gas cloud was detected in W in a given time t by several sensors – nodes of the network $\mathscr{G}$. These sensors create a subnetwork located inside the cloud $\mathscr{G}' = (\mathscr{V}', \mathscr{E}')$ and exchange information with the network $\mathscr{G}$ head H using multi-hop connections. The messages broadcasted by nodes $D_i \in \mathscr{G}'$ contain information about their current positions in the workspace W. It is assumed that each network node is equipped with the tool for location calculation.
After collecting messages from established number of sensing devices H estimates the location of the gas cloud center $\mathbf{c}_c$ (a centroid of $\mathscr{G}'$) based on data received from $D_i \in \mathscr{G}'$.

$$\mathbf{c}_c = \frac{\sum_{D_i \in \mathscr{V}'} \mathbf{c}^i}{|\mathscr{V}'|}. \tag{13}$$

H estimates the initial reference distance to the centroid $\overline{d}_c = \max_{D_i \in \mathscr{V}'} d^i_c + w_1$, where $w_1 > 0$ denotes a distance margin and d^i_c a distance between c_c and c^i. Next, H distributes both $\mathbf{c}_c$ and $\overline{d}_c$ across the whole network $\mathscr{G}$.

Phase 3 – sensing devices optimal deployment. The aim is to surround the most of the detected gas cloud by sensors and track its boundary. In general, in presented computing schemes the construction of MANET for cloud boundary tracking is composed of following steps executed repetitively:

- data exchange between the head of MANET and all other sensing devices,
- a gas cloud centroid update,
- attraction of sensing devices inside the gas cloud,
- connectivity maintenance and redundant network nodes detection,
- optimal displacements of network nodes calculation.

All sensing devices with positions outside the gas cloud are attracted by the gas cloud centroid. They are forced to move to the region covered by the cloud. Their new positions are calculated solving the optimization problem (12) for $\mathbf{c}^i_g = \mathbf{c}_c$ and $\overline{d}^i_g = \min_{D_i \in \mathscr{V}'} \overline{d}^i_c$, $i = 1, \ldots, N$.
Next, each sensing device estimates its own position and the optimal displacements for all nodes are calculated. Two computing schemes – centralized and distributed – have been developed for calculating the optimal positions of all devices and create the optimal network topology for a given gas cloud boundary tracking.

5. Centralized Algorithm for Sensing Devices Deployment

Let us assume that the goal is to create sensing system for regular cloud boundary detecting and tracking by sensor devices equipped with the same quality radio transceivers. Authors establish as a target point in Eq. (12) the centroid of a gas cloud calculated based on preliminary cloud exploration, i.e. $\mathbf{c}_g^i = \mathbf{c}_c$, $i = 1, \ldots, N$ i provided. Furthermore, the same similar value of $\overline{d}_g^i = \overline{d}_c$ for all D_i and values of $\overline{d}_j^i$ slightly smaller than the transmission range $\overline{d}_j^i \leq r_t$, $i, j = 1, \ldots, N$ is provided.

The mobility model (12) induces all devices to move in the advisable direction to cover the region of interest by the coherent network of sensing devices. The objective is to track and estimate the boundary of the cloud, not to explore the inside of this cloud. Therefore, some modifications to the model (12) have been proposed. To surround most of the cloud authors have to elbow all devices, repulse from the centroid $\mathbf{c}_c$, and force them to move and take positions on the cloud boundary. Hence, the number of neighboring nodes for i-th device (a set S_i) should be reduced to two. Two neighboring nodes are enough to maintain permanent connectivity with the network head H. To create the optimal topology for cloud boundary tracking the redundant nodes have to be detected, removed from the set S_i and shifted away. The following procedure for detecting and removing redundant links has been developed. The inspirations came from [17], [38], [39]. Let us define two coverage regions for the i-th transceiver: safe (cov_s^i) and critical (cov_c^i):

- cov_s^i denotes a disc of a radius r_t^s, $r_t^s < r_t$ centered at the transmitter.
- cov_c^i denotes a set of points with distance d_j^i to $\mathbf{c}^i$ satisfying the condition $r_t^s \leq d_j^i \leq r_t$.

We assume that all nodes located in cov_c^i can be critical for maintaining connectivity with the i-th node and the special attention should be paid on the calculation of their displacements.

The information about the current status of each node is provided by the network head H. Next, the set $C_i(t)$ of critical neighbours of the i-th node every timestep t is created. The network head H removes the link (i, j) from $\mathscr{E}(t)$ and creates a new graph $\mathscr{G}^*$. Next, the laplacian matrix L^* is determined:

$$L^* = \Delta^* - A^*, \tag{14}$$

where $A^* = (a_{ij}^*)$ denotes the adjacency matrix of the graph $\mathscr{G}^*$. $a_{ij}^* = 1$ if $(D_i, D_j) \in \mathscr{E}^*$ and 0 otherwise, $\Delta^* = diag(\sum_{j=1}^{n} a_{ij}^*)$. The eigenvalues λ_i^* of the matrix L^* are calculated and sorted in ascending order

$$\lambda_1^* \leq \lambda_2^* \leq \ldots \leq \lambda_N^*. \tag{15}$$

Due to [17] the graph $\mathscr{G}^*(t)$ is connected for $\lambda_2^* \geq 0$. It means that the node j-th does not influence the connectivity – it is redundant and can be removed from the set $S_i(t)$. Otherwise, the j-th node is critical and can not be removed from the set C_i. To preserve connectivity all devices $D_j \in C_i \neq \emptyset$, $j = 1, \ldots, N$ are attracted to D_i. They are forced to move and take position in the region cov_s^i.

Finally, each device computes its new position in the workspace W. Depending on the position of the node two phases are distinguished. In case of $D_j \in C_i$ the node D_j is the critical one for connectivity maintenance, and is attracted to D_i. New position of the j-th node is calculated solving the optimization problem (12) for $U^j = \sum_{D_m \in C_j, m \neq j} U_m^j$.

After moving all critical nodes to the safe regions and ensuring the network connectivity new positions of all nodes are calculated to detect and track the boundary of the cloud.

6. Distributed Algorithm for Sensing Devices Deployment

In centralized deployment all calculations are performed by the network head H based on data gathered from all other network nodes. The main drawback of such computing

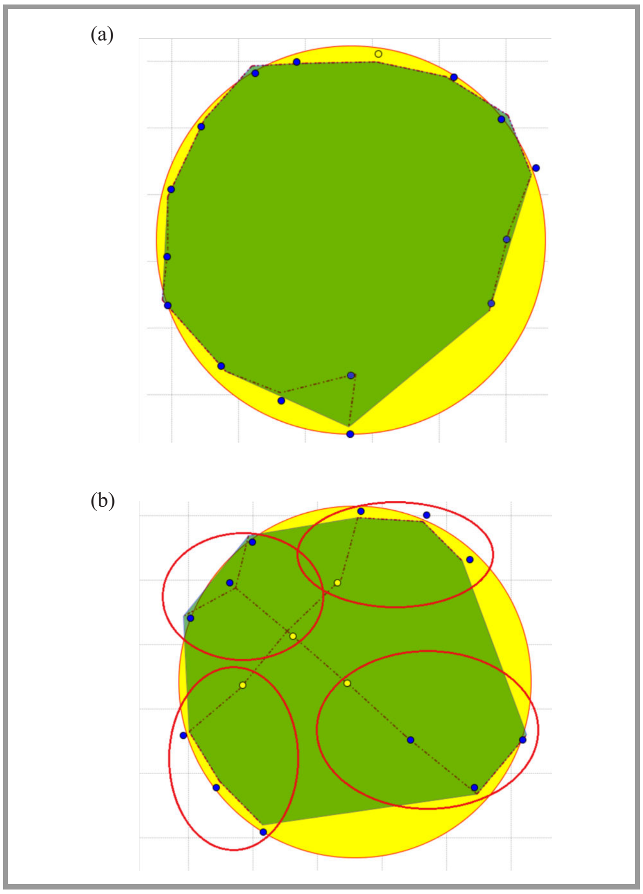

Fig. 1. Sensing network topologies: (a) centralized deployment, (b) distributed deployment, $k = 4$. (See color pictures online at www.nit.eu/publications/journal-jtit)

scheme is a significant amount of messages that have to be exchanged among all devices (nodes' positions, updated $\mathbf{c}_c$ and $\overline{d}_c$, connectivity messages, etc.). Furthermore, it is impossible to surround a large gas cloud by limited number of devices with low quality transceivers. Nodes tend to create *half ring* topology (Fig. 1a), which causes unbalanced communication load – the closer the head H the node is, the more messages has to relay. The solution is a network composed of heterogeneous devices and division of a set of devices $\mathscr{V}$ into K separated clusters of devices:

$$\mathscr{V}_1 \cup \mathscr{V}_2 \cup \ldots \cup \mathscr{V}_K = \mathscr{V} \tag{16}$$

$$\mathscr{V}_1 \cap \mathscr{V}_2 \cap \ldots \cap \mathscr{V}_K = \emptyset \tag{17}$$

In each cluster $\mathscr{V}_k$, $k = 1, \ldots, K$ a device equipped with the most powerful transceiver is nominated for a cluster head $H_k \in \mathscr{V}_k$. The network head H belongs to this group. Only cluster heads are responsible for maintaining a permanent connectivity with H. Devices from the cluster $\mathscr{V}_k$ create a sensing subnetwork $\mathscr{G}_k$. Thus, to maintain the connectivity within a network the following requirements have to be satisfied:

- a permanent connectivity inside each subnetwork $\mathscr{G}_k$ has to be maintained,
- a permanent connectivity between all cluster heads has to be maintained.

Each device repetitively calculates its new position in the workspace W. The following optimization problem, that is a modified version of the problem (12), is solved by the i-th device that is a member of the mth cluster, $D_i \in \mathscr{V}_m$:

$$\begin{aligned}\min_{\mathbf{c}^i} \Bigg[U^i &= U_g^i + \sum_{D_j \in S_i, D_j \in \mathscr{V}_m} U_j^i + \sum_{k \in IC_m} U_k^i \\ &= \varepsilon_g \left(\frac{\overline{d}_g^i}{d_g^i} - 1 \right)^2 + \sum_{D_j \in S_i, D_j \in \mathscr{V}_m} \varepsilon_j \left(\frac{\overline{d}_j^i}{d_j^i} - 1 \right)^2 \\ &\quad + \sum_{k \in IC_m} \varepsilon_k \left(\frac{\overline{d}_k^i}{d_k^i} - 1 \right)^2 \Bigg],\end{aligned} \tag{18}$$

where IC_m is a set of indexes of two closest neighboring clusters of m-th cluster that contains D_i, defined as:

$$IC_m = \left\{ \underset{\mathscr{V}_j \neq \mathscr{V}_m}{\arg\min} \sphericalangle(\mathscr{V}_m, \mathscr{V}_j) \right\} \cup \left\{ \underset{\mathscr{V}_j \neq \mathscr{V}_m}{\arg\max} \sphericalangle(\mathscr{V}_m, \mathscr{V}_j) \right\} \tag{19}$$

$$\sphericalangle(\mathscr{V}_m, \mathscr{V}_j) = \begin{cases} \arccos \frac{\overrightarrow{\mathbf{c}_c\mathbf{c}_m} \cdot \overrightarrow{\mathbf{c}_c\mathbf{c}_j}}{|\mathbf{c}_c\mathbf{c}_m| \cdot |\mathbf{c}_c\mathbf{c}_j|} & \overrightarrow{\mathbf{c}_c\mathbf{c}_m} \times \overrightarrow{\mathbf{c}_c\mathbf{c}_j} \geq 0 \\ 2\Pi - \arccos \frac{\overrightarrow{\mathbf{c}_c\mathbf{c}_m} \cdot \overrightarrow{\mathbf{c}_c\mathbf{c}_j}}{|\mathbf{c}_c\mathbf{c}_m| \cdot |\mathbf{c}_c\mathbf{c}_j|} & \overrightarrow{\mathbf{c}_c\mathbf{c}_m} \times \overrightarrow{\mathbf{c}_c\mathbf{c}_j} < 0 \end{cases} \tag{20}$$

$$\mathbf{c}_m = \frac{\sum_{D_i \in \mathscr{V}_m} \mathbf{c}^i}{|\mathscr{V}_m|}. \tag{21}$$

The idea of selecting the closest clusters is illustrated in Fig. 2. In the presented example D_i belongs to the cluster $\mathscr{V}_4$. The set IC_m contains indexes of clusters $\mathscr{V}_1$ and $\mathscr{V}_3$.

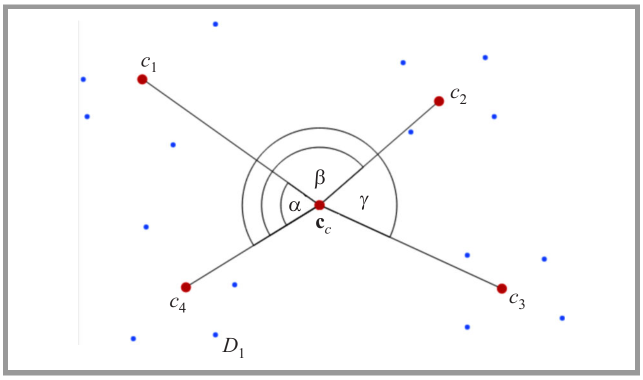

Fig. 2. Illustration of two closest clusters selection; angles to be considered in Eq. (19): $\sphericalangle(\mathscr{V}_4, \mathscr{V}_1) = \alpha$, $\sphericalangle(\mathscr{V}_4, \mathscr{V}_2) = \beta$, $\sphericalangle(\mathscr{V}_4, \mathscr{V}_3) = \gamma$.

Node D_i will be forced to move to such position in which the distance to centroids of clusters $\mathscr{V}_1$ (point $\mathbf{c}_1$) and $\mathscr{V}_3$ (point $\mathbf{c}_3$) are similar. Hence, D_i will be repulsed from the centroid of the closer cluster ($\mathscr{V}_1$) and will be attracted by the further cluster ($\mathscr{V}_3$).

To ensure even distribution of clusters the distance $\overline{d}_m^i$ is defined as an average distance between two clusters with indexes from IC_m increased by a distance margin w_2 (slightly greater than 0)

$$\overline{d}_m^i = \frac{\sum_{k \in IC_m} \overline{d}_k^i}{2} + w_2, \qquad w > 0, \tag{22}$$

where $\overline{d}_k^i$ is the real Euclidean distance between $\mathbf{c}^i$ and $\mathbf{c}_k$.

Figure 1a shows a network topology created according to centralized computing scheme. The results of distributed computing scheme, i.e. four clusters with ring-marked cluster heads are presented in Fig. 1b. It can be observed that in topologies created according to the distributed strategy the cluster heads are located inside the cloud serving as higher-level communication layer.

7. Case Study Results and Performance Evaluation

A numerous simulation experiments were conducted in order to present the efficiency of proposed approaches for design of MANET for detecting and boundary tracking of heavy gas cloud. All experiments were performed using the MobAsim framework for mobile ad hoc networks simulation described in [13].

7.1. Simulation Scenarios

The following emergency situation was simulated. A tank crash caused an instantaneous release of chlorine gas and environmental damage. The goal was to detect, surround and suppress a chlorine gas cloud. The emergency team

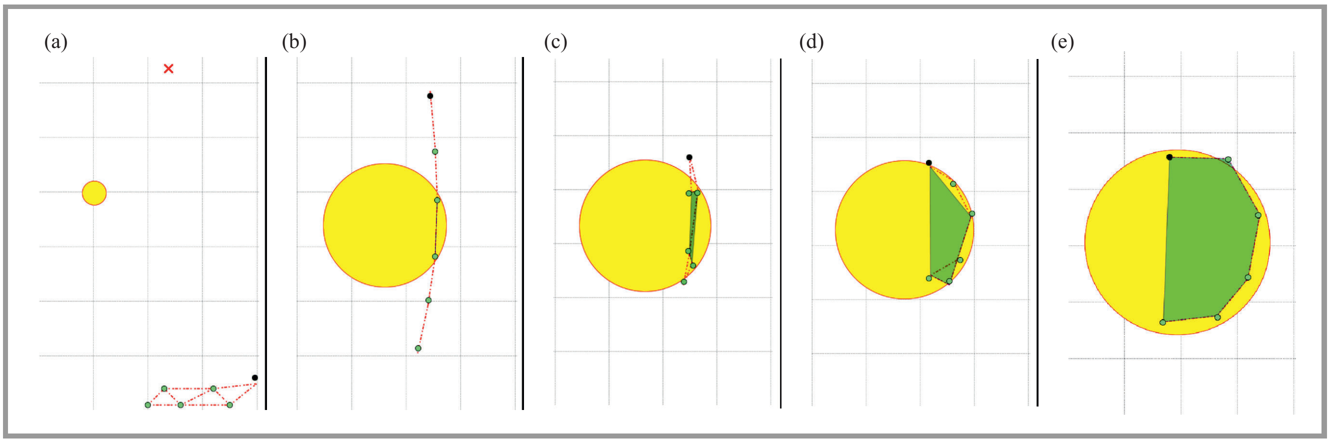

Fig. 3. Initial, temporal and final topologies of the MANET for heavy gas cloud boundary tracking.

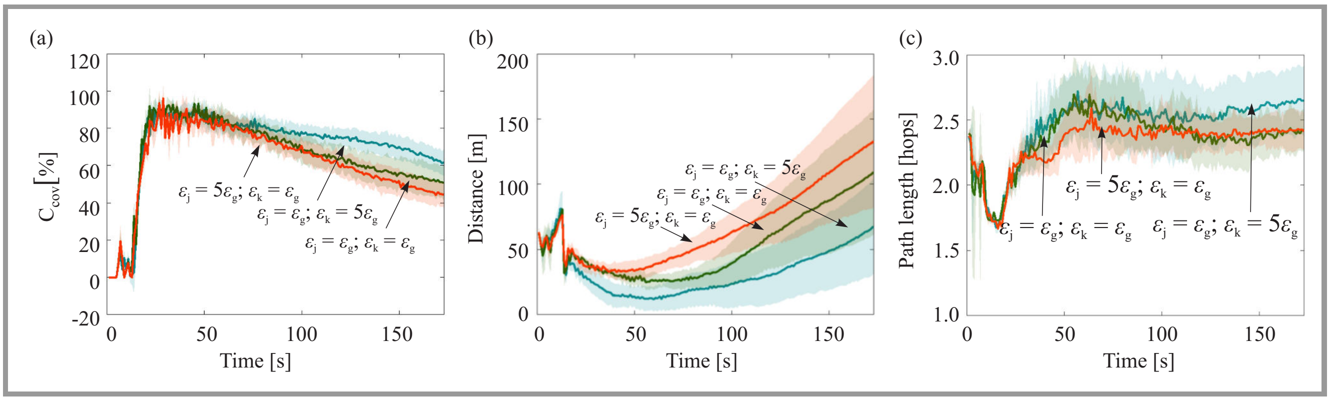

Fig. 4. Quality of network topologies for various values of parameters ε_j and ε_k: (a) average coverage rate, (b) distance between estimated and real centroid of a cloud, (c) average path between a node and a network head.

comprised of self-organized wireless mobile devices carrying punctual gas sensors was employed to perform this task.

Various topologies of sensing networks created using centralized and decentralized strategies were evaluated and compared according to the following criteria:

1. The percent of a gas cloud coverage by a given MANET
$$C_{cov} = \frac{cov_{\mathcal{G}}}{cov_{GC}} \cdot 100\%\,, \tag{23}$$
where C_{cov} is the percent of a surface of a gas cloud detected by MANET, cov_{GC} denotes a real surface of the gas cloud, $cov_{\mathcal{G}}$ an area of a polygon with boundary discovered by all sensing devices (the network $\mathcal{G}$);

2. The distance between the centroid of detected cloud $\mathbf{c}_c$ and the centroid of the real cloud $\bar{\mathbf{c}}_c$;

3. The average path length between each node and a network head H.

7.2. Illustration of the Deployment Process

The steps of sensing network comprised of six devices creation process are illustrated in Fig. 3a-e. The initial topology and the location of released gas cloud are presented in Fig. 3a. The black node represents the head of a network. In the exploration phase the head was forced to the randomly selected direction, while other nodes followed him. After detecting the gas cloud (Fig. 3b) all nodes located outside the cloud were forced to move inside the cloud. They were attracted by the estimated centroid of the cloud. The preliminary sensing topology was created (Fig. 3d). Finally, the devices self-organized themselves to cover the most of the boundary of the cloud and were tracking this boundary. The final topology is presented in Fig. 3e.

7.3. Distributed and Centralized Deployment

In the first series of experiments the distributed scheme was applied to generate sensing network topology. The goal was to tune the number of clusters and parameters ε_g, ε_j, ε_k in (18). The set of devices was divided into four groups ($k = 4$) and ε_g was set to 1000. The topologies for various values of ε_j and ε_k were compared. The results are presented in Fig. 4. It can be seen that the best results were obtained for $\varepsilon_k > \varepsilon_j$. The exemplary final topologies are depicted in Fig. 5.

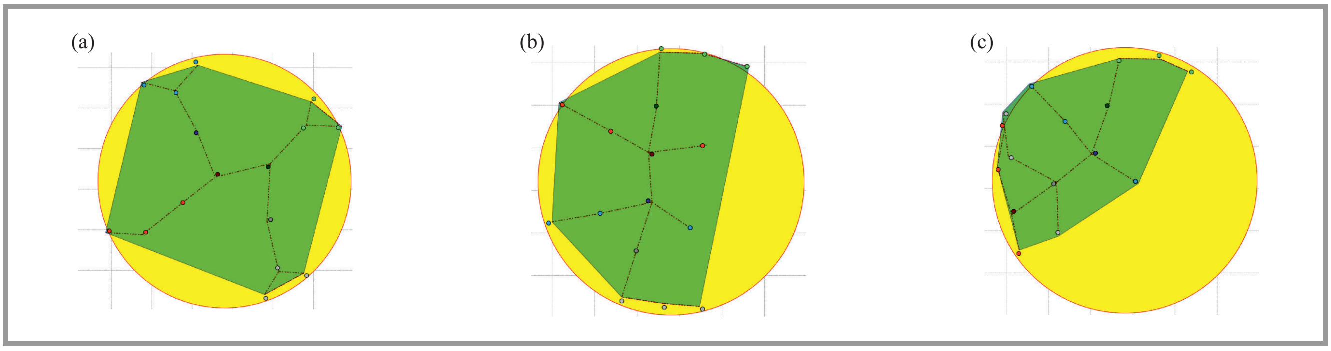

Fig. 5. MANET topologies ($t = 180$, $K = 4$) for various values of parameters: (a) $\varepsilon_j = \varepsilon_g$ and $\varepsilon_k = 5\varepsilon_g$, (b) $\varepsilon_j = \varepsilon_g$ and $\varepsilon_k = \varepsilon_g$, (c) $\varepsilon_j = 5\varepsilon_g$ and $\varepsilon_k = \varepsilon_g$.

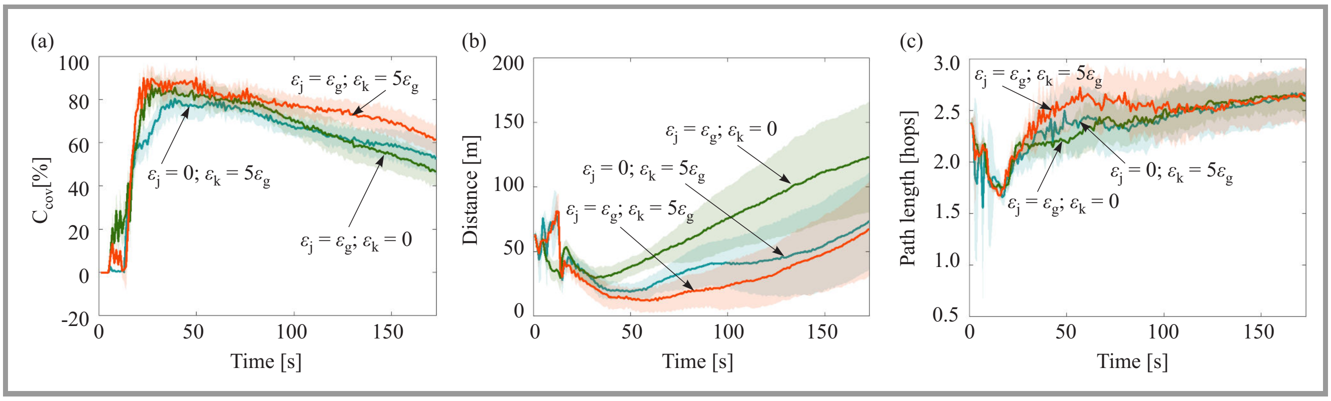

Fig. 6. Quality of network topologies for various values of parameters ε_j and ε_k: (a) average coverage rate, (b) distance between estimated and real centroid of a cloud, (c) average path between a node and a network head.

Then, two series of experiments for $\varepsilon_j = 0$, $j = 1, \ldots, |\mathscr{V}_k|$ and $\varepsilon_k = 0$, $k = 1, \ldots, K$ were conducted, respectively. The results are presented in Fig. 6. In general, it was observed that the accuracy of the cloud centroid detection was much better when interactions between clusters were taken into account in calculation process, i.e. $\varepsilon_k > 0$. Moreover, repulsion within a cluster (i.e. $\varepsilon_j > 0$) increased network coverage. Exemplary final topologies calculated for $\varepsilon_j = 0$ or $\varepsilon_k = 0$ are presented in Fig. 7.

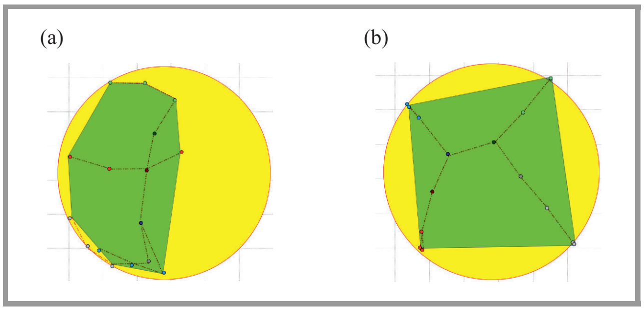

Fig. 7. MANET topologies ($t = 180$, $K = 4$) for various values of parameters: (a) $\varepsilon_j = \varepsilon_g$ and $\varepsilon_k = 0$, (b) $\varepsilon_j = 0$ and $\varepsilon_k = 5\varepsilon_g$.

Next, the influence of number of clusters on the efficiency of sensing network system was tested. The results for various number of clusters are presented in Fig. 8. Comparison of topologies generated for different values of K are shown in Fig. 9. In general, the simulation results confirm the assumption that the number of clusters should be tuned to the total number of sensing devices. In case of small set of devices the number of clusters should be limited.

Finally, the distributed deployment strategy was compared with the centralized one. Figure 10 presents values of criteria defined in Subsection 7.1 obtained for both approaches. The application of distributed algorithm significantly shortened the average path length between nodes and network head. It should be pointed that the shorter path length and the aggregation of transmitted data by cluster heads reduce the communication cost. The final coverage of a gas cloud was similar both in centralized and distributed computing schemes.

8. Summary and Conclusions

Modern sensing systems can be created by sensors mounted on mobile platforms, i.e., unmanned vehicles, mobile robots or drones, moved to desirable positions. It is obvious that mobility implies an additional complexity layer. However, the complexity of sensing systems design, implementation

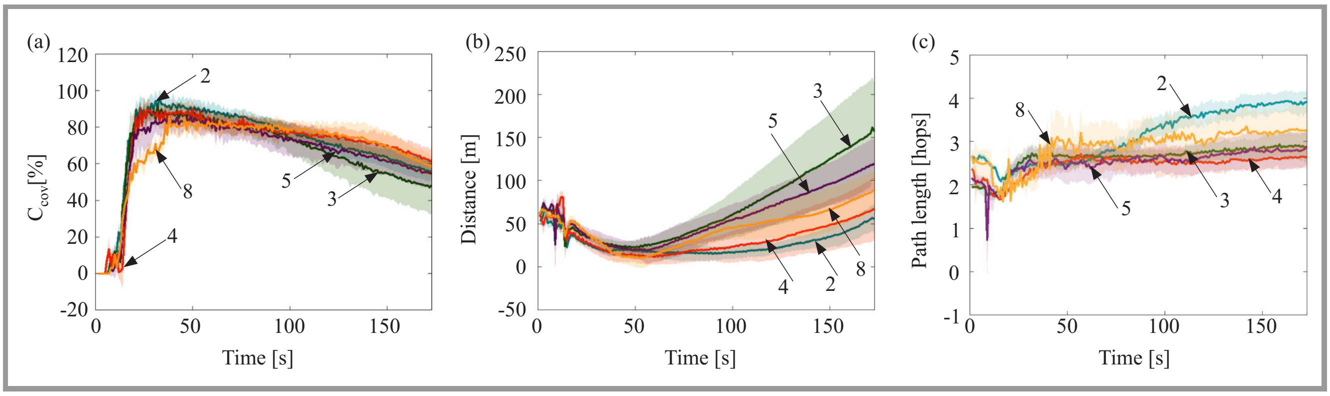

Fig. 8. Quality of network topologies for various number of clusters, $\varepsilon_j = \varepsilon_g$ and $\varepsilon_k = 5\varepsilon_g$: (a) average coverage rate, (b) distance between estimated and real centroid of a cloud, (c) average path between a node and a network head.

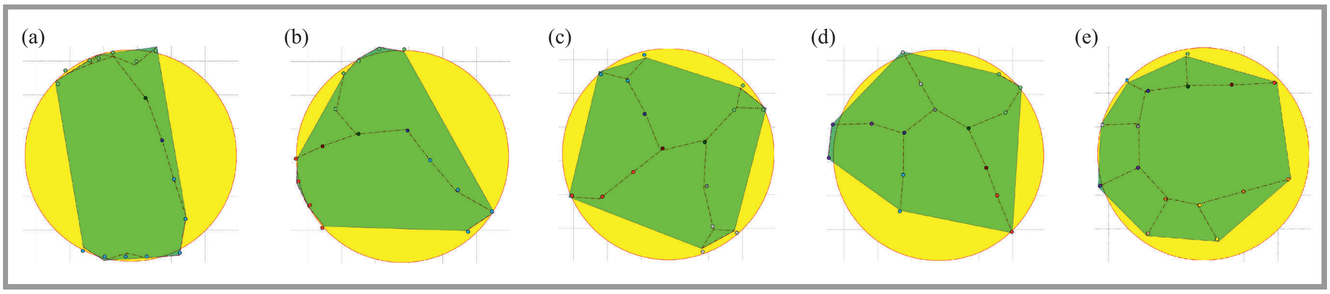

Fig. 9. MANET topologies ($t = 180$) for various number of clusters: (a) $K = 2$, (b) $K = 3$, (c) $K = 4$, (d) $K = 5$ and (e) $K = 8$.

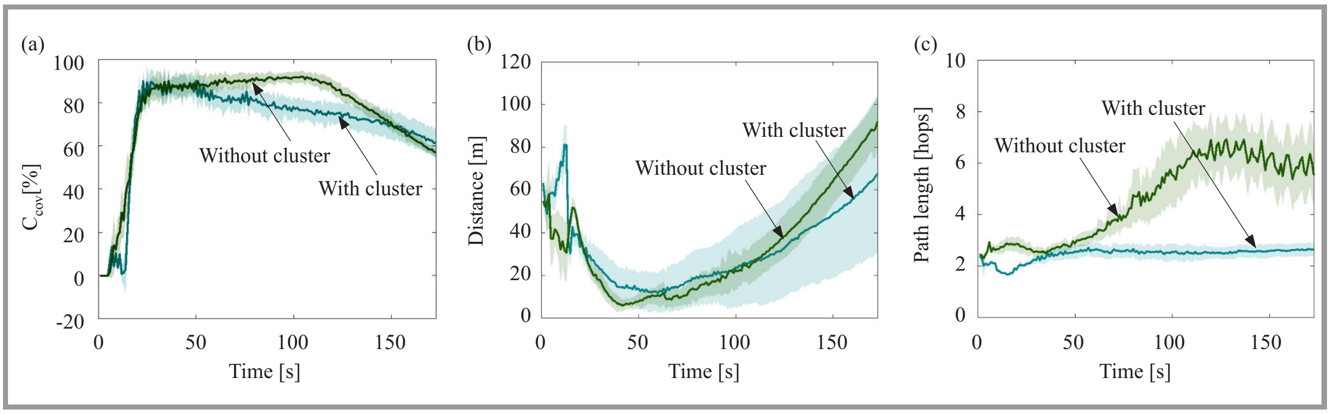

Fig. 10. Comparison of centralized and distributed deployment strategies.

and management is compensated by a number of benefits. Endowing network nodes with mobility drastically expands sensing networks capabilities. Mobility allows to detect lacks of deployment objectives, improve coverage and communication connectivity even decreasing number of employed sensing devices. A large number of measurement targets can be handled with smaller number of migrating sensors.

In this paper two computing schemes for construction of mobile sensing system for heavy gas cloud detection and boundary tracking are described. These schemes utilize centralized and distributed strategies for calculating the desired positions of all sensing devices in a region of interest. Both developed algorithms were implemented in the simulation platform and verified through extensive simulation experiments. The presented case study shows that presented algorithms can be successfully used to design self-configuring and coherent networks for monitoring and tracking purposes. Moreover, the efficiency of monitoring can be increased by enabling clustering methods.

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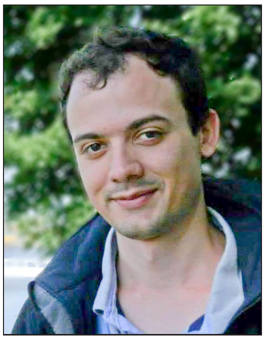

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