# Mobility Model for Self-Configuring Mobile Sensor Network

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***Abstract*—A self-configuring sensor network is a collection of wireless devices that collaborate with each other to form a network system that adapts to achieve a goal or goals. Such network is often built from mobile sensors that may spontaneously create a network and dynamically adopt to changes in the unknown environment and network requirements. Mobility pattern is a critical element that influences the performance characteristics of mobile sensor networks (MSN). In this paper, we discuss main directions to mobility modeling and present a systematic taxonomy of the mobility models that is provided in literature. Finally, we describe a novel algorithm for calculating mobility patterns for mobile devices that is based on a cluster formation and an artificial potential function. Our model can be used both to a simulation-based design of MSN, and to a motion planning for real, physical MSN. The presented simulation study for a rescue mission planning illustrates the possible application of our model.**

***Keywords*-self-configuring network; mobile sensor network; mobility models; potential field;**

## I. Introduction

In the last years, wireless sensor networks (WSN) have gained increasing attention from both the research community and users [3], [11]. WSN are distributed architectures formed by a set of wireless devices that can freely and dynamically organize themselves into temporary network topologies. Typical WSN usually consists of stationary devices. In many real life applications networks formed by stationary nodes suffer insufficiency. Therefore, there is a need for mobile sensor network (MSN) that is capable to change its layout and position. Such a network is formed by mobile sensor devices.

This paper considers issues concerning self-configuring MSN design and development. We focus on network systems formed by mobile, wireless devices that may spontaneously create a network, manage movement of sensor nodes, assemble the network themselves, dynamically react to changes in the domain and network requirements. There are many benefits of these features, and many potential applications. Examples include an optimal coverage for monitoring of an unknown environment, producing a well connected network despite the limited resources, providing a connection between data sources and data sinks, which are not necessarily uniformly distributed across the network, and others. It is obvious that the mobility of MSN can be used to improve its performance characteristics, such as sensing coverage or network connectivity. The question is how the mobility can efficiently be managed toward a better network system performance. We present and describe a novel approach to design MSN. The proposed concept of mobility patterns calculation is based on a cluster formation and an idea of potential function commonly used in robots navigation.

## II. Mobility modeling in MSN

Modeling of node mobility plays the crucial role in design and development of MSN systems. Simulation results show that the communication protocols performance may vary drastically across mobility models and performance rankings of protocols may vary with the mobility models used [1], [7]. Therefore, studying the performance of ad hoc networking protocols and application services in the presence of mobility is an important stage of the design process. It implies that the characteristics of mobility models of mobile nodes need to be analyzed and studied very carefully. It is obvious that real-life movement patterns are very difficult to obtain, and realistic models are usually very complicated. Many less and more detailed mobility models have been introduced, and are described in literature. The survey can be found in [7].

In this paper, we present the mobility models taxonomies provided in [1] and [7]. In general, we can distinguish two approaches for mobility patterns modeling [2], [7], [8]:

- *Motion traces models* (TM). The deterministic models, that require the accurate information about mobility patters (i.e., positions of nodes in time).
- *Syntactic models* (SM). The analytical random-motion models, that uses randomness in calculation of traversing patterns from one place to another. They can be classified based on the description of the mobility patterns into: individual mobile movements and group mobile movements, and based on the degree of randomness into: constrained topology-based models and statistical models. In constrained topology-based models the movement is restricted by various constraints:

pathways, speed limits, obstacles, etc. In statistical model the node is allowed to move anywhere in the domain, hence the model is based on total randomness.

Bai et al. [1] classify the mobility models based on their basic mobility characteristics:

- *Random models*. As in statistical models, nodes move randomly, and can be classified further based on the degree of randomness. A Random Mobility model (RM) that implements Brownian-like motion, and a Random Waypoint model (RWP) with randomly generated destination point and velocity are popular models from this group.
- *Models with temporal dependency*. The mobility patterns are influenced by the previously generated movement patterns. A Gauss-Markov and smooth random mobility model fall into this category.
- *Models with spatial dependency*. The nodes tend to move in a correlated manner. A reference point group mobility model belongs to this category.
- *Models with geographical restrictions*. The movements of all nodes are constrained by streets, roads, obstacles, etc. Path-based and obstacle mobility models fall into this category.

Roy [7] provides the alternative classification. He divides the models into seven groups:

- *Individual mobility models*. The mobility pattern for the individual node is calculated.
- *Group mobility models*. The mobility pattern for a group of cooperative nodes is calculated.
- *Autoregressive mobility models*. The mobility patterns are correlated with the mobility states (i.e.: position, velocity, acceleration at consecutive time instants).
- *Flocking and swarm mobility models*. The mobility patterns imitate the trajectories performed by dynamic nodes of self-organizing networks in nature (like swarms).
- *Virtual game-driven mobility models*. The mobility pattern calculation takes into account the interactions with all other nodes in a network or with groups of nodes.
- *Non-recurrent mobility models*. It is assumed that a network permanently changes its topology in time. A node moves in a totally unknown way, and previous patterns are not repeated.
- *Social-based mobility models*. The family of the mobility models that are associated as a community of groups within a society. The models describe non-homogenous behaviors in both space and time.

The mobility models that are examples of above-quoted categories of models are collected in Table I.

Table I
MOBILITY MODELS.

| Group of models | Models |
|---|---|
| Individual mobility models | Random walk mobility |
| | Random waypoint mobility |
| | Smooth random mobility |
| | Geographic constraint mobility |
| | Realistic random direction mobility |
| | Deterministic mobility |
| | Partially deterministic mobility |
| | Random Gauss-Markov mobility |
| | Semi-Markov smooth mobility |
| | Steady-state generic mobility |
| | Graph-based mobility |
| | Hierarchical influence mobility |
| | Boundless simulation area mobility |
| | Behavioral mobility |
| | Fluid-flow mobility |
| | Potential field mobility |
| | Correlated diffusion mobility |
| | Particle-based mobility |
| Group mobility models | Reference point mobility |
| | Reference velocity mobility |
| | Reference velocity |
| | & acceleration mobility |
| | Structured mobility |
| | Virtual track-based mobility |
| | Drift mobility |
| | Group force mobility |
| Autoregressive models | Autoregressive individual mobility |
| | Autoregressive group mobility |
| Flocking and swarm models | Flocking mobility |
| | Swarm group mobility |
| Virtual game-driven models | Virtual game-driven mobility |
| | Virtual game-driven mobility |
| Non-recurrent models | Non-recurrent mobility |
| Social-based models | Time-variant mobility |
| | Community-based mobility |
| | Orbit-based mobility |
| | Entropy-based mobility |
| | Knowledge-driven mobility |

## III. MOBILITY MODEL FOR SELF-CONFIGURING MSN

We consider a problem of design a self-configuring network of mobile nodes, connected by wireless links. We assume that to achieve a goal network nodes should collaborate, and a whole network should enable continuous communication with the base station, hence the network must be connected. Collective motion is often required in mobile sensing networks. It involves communication among and between individual nodes or clusters of nodes to coordinate their movement. We assume that the network system should change its topology to achieve a goal. The objective is to calculate mobility patterns for all network nodes. The use of relatively simple random mobility models did not give satisfactory results in our experiments. Therefore, we have developed a novel algorithm to calculate mobility patterns for a mobile sensor network. Our mobility model resembles a collision-free movement of a group of mobile devices. It can be used in ad hoc networks simulation for design of

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network scenarios or for motion planning for real MSN.

In our research we have focused on the individual mobility where the mobility pattern of an individual node is considered. Our model combines two approaches – *potential field* and *particle-based mobility modeling*. The concept to build an artificial potential field where the mobile devices move from a *high-value* state to a *low-value* state, and define an associated potential function that captures both operational goals and the environment of a network is a popular direction in motion planning in mobile robotics [4], and mobile sensor networks [5]. Due to such model, the determined mobility pattern of each node includes attraction to the destination and repulsion from each obstacle. In these approaches sensor nodes not only receive forces from the surrounding environment, but also receive forces from one another. The particle-based mobility modeling [7] that considers each mobile node as a "self-driven" moving particle in the physics of Newtonian mechanics or quantum mechanics is the other popular technique in management of mobile devices. Each node is characterized by a sum of forces, describing its desire to move to the direction, avoiding collisions with other nodes and obstacles. The driving force is associated with each node, and is self-produced.

### A. *Problem Formulation and Network System Description*

Let us consider a set of mobile wireless devices that compose MSN, and are assumed to operate in a three-dimensional field filled with obstacles. Each node navigates itself to a particular location to achieve the goal. The objective is to calculate the optimal motion trajectory from one configuration to another that meets the following requirements:

1) the mobility should be managed toward a better coverage and well connected network that enables a continuous communication with a base station,
2) the traversing pattern from one place to another has to be collision free and should allow to push the network node through the narrow passage,
3) the traversing pattern has to capture the environment requirements (the signal propagation can change in time).

We propose the scheme for management of nodes' movement based on a cluster formation and application of an artificial potential function that captures the above-quoted requirements. In our formulation all network nodes and obstacles form a set $S$ of $N$ entities; $O_i$, $i = 1, \ldots, N$. We assume that our obstacles can move as well (nodes can be obstacles for other nodes in the network), hence the obstacles are the same type of entities as the network nodes. We define each entity $O_i$ as a solid body, which position is described by three Cartesian coordinates $[x_i, y_i, z_i]$ and orientation is given by a quaternion [4]: $Q^i = q_0^i + q_1^i\mathbf{i} + q_2^i\mathbf{j} + q_3^i\mathbf{k}$. We consider objects that are of different shapes. To simplify the calculation we made an assumption that the interactions

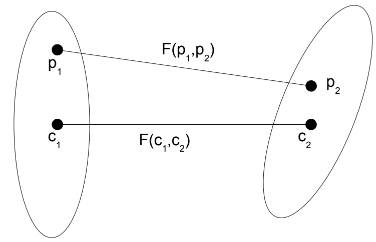


Figure 1. The node description.

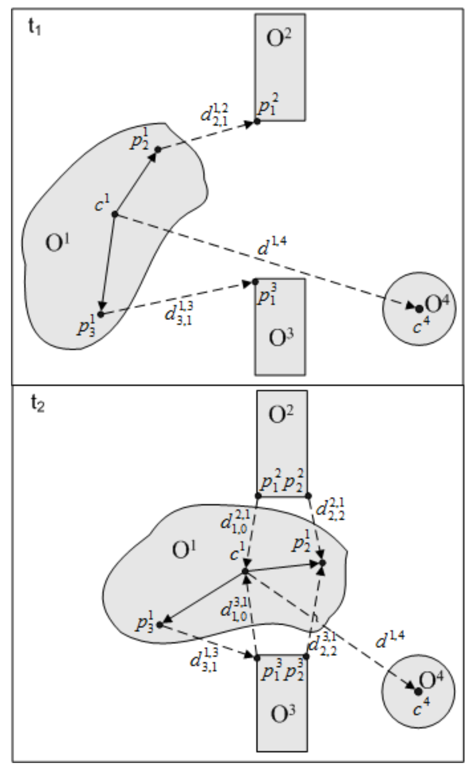


Figure 2. The rotation of the mobile device.

between each pair of entities ($O_i$ and $O_j$) are described by the interactions between points selected from $O_i$ and $O_j$ (see Fig. 1). Hence, in case of $O_i$ the set of selected points is as follows: $P^i = \mathbf{p}_i^1, ..., \mathbf{p}_M^i$, $P^i \in O^i$, with $\mathbf{p}_1^i = \mathbf{c}^i$, where $\mathbf{c}_i$ is the central point, and $M_i$ - 1 other points are selected by the user. Such a representation of a node allows us to implement translation and rotation, hence it is easy to rotate the network node and push through the narrow passage, Fig. 2. The rotation is given by a quaternion product.

Obviously, it is possible to simplify the description, – each object $O_i$ can be described by a single point $\mathbf{c}_i$ (similarly to commonly used mobility models). In such an approach the mobility pattern calculation simplifies, but the generated trajectory is less realistic.

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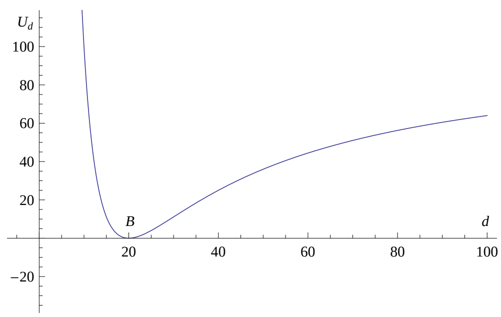


Figure 3. The artificial potential function.

### B. Potential Field Mobility Model

Inspired by classical dynamics that study the motion of objects in the concept of an artificial potential fields, and particle-based modeling we propose the model in which the mobility of each node in the network is governed by the description of an artificial potential function. The potential function $U$ is a differentiable real valued function, which value can be viewed as an energy, and hence the gradient of the potential is a force. The gradient is a vector, which points in the direction that locally maximally increases $U$. The potential function can be constructed as a sum of attractive and repulsive potentials. The meaning of the attractive/repulsive is straightforward: the goal attracts the mobile device while the obstacle repels it. Therefore, the sum of attractive and repulsive influences draws the mobile device to the goal while deflecting it from obstacles. The *gravity mobility model*, which is based on the use of Newton's gravitational law of motion in classical dynamics to calculate a mobility pattern is the example of this approach. Unfortunately, it is insufficient in many applications. The model often introduces oscillations into the movement of nodes. The oscillations are hard to eliminate. To address this problem, we constructed a simple potential function that captures all the requirements for calculated mobility pattern mentioned in the previous paragraph. The inspiration came from classical mechanics and liquid crystals where it is popular to model the interactions between a pair of neutral atoms or molecules via Lennard-Jones potential function (see [10] for details). We propose the simpler function with similar characteristics:

$$U_{ab}^{ij}(\hat{d}_{ab}^{ij}) = \begin{cases} \epsilon m_a^i m_b^j \left(\frac{\bar{d}_{ab}^{ij}}{\hat{d}_{ab}^{ij}} - 1\right)^2 & |\bar{d}_{ab}^{ij} - \hat{d}_{ab}^{ij}| > \tau_{ab}^{ij} \\ 0 & |\bar{d}_{ab}^{ij} - \hat{d}_{ab}^{ij}| \le \tau_{ab}^{ij} \end{cases} \tag{1}$$

where $\hat{d}_{ab}^{ij}$ denotes the estimated distance between points $\mathbf{p}_a^i$ and $\mathbf{p}_b^j$, $\bar{d}_{ab}^{ij}$ the reference inter-node distance (calculated due to maximal radio range), $\epsilon$, $m_a^i$, $m_b^j$ and $\tau_{ab}^{ij}$ are parameters. The point reaches an unstable equilibrium for $\hat{d}_{ab}^{ij} \in [\bar{d}_{ab}^{ij} - \tau_{ab}^{ij}, \bar{d}_{ab}^{ij} + \tau_{ab}^{ij}]$, as depicted in Fig. 3. Similarly to the Lennard-Jones potential the form of $U_{ab}^{ij}$ has no theoretical justification. In the reference position of our node $\hat{d}_{ab}^{ij} = \bar{d}_{ab}^{ij}$ we obtain $U_{ab}^{ij} \approx 0$; it means the best coverage on condition of full connected network. However, in unknown environment with obstacles it is usually impossible to move a node to an optimal position. Hence, we can calculate the estimated distance $\hat{d}_{ab}^{ij}$ solving the optimization problem

$$\min_{\hat{d}_{ab}^{ij}} U_{ab}^{ij}(\hat{d}_{ab}^{ij}) \tag{2}$$

It is obvious that the calculation of the whole trajectory since the node reaches the equilibrium point is not an easy task because of the numerous actors operating in the scene. However, we can describe our mobile network as a physical system consisting of objects that are forced to move in the advisable direction with the adequate speed. The **algorithm 1** for traversing pattern calculation at time instants $t_0 + \Delta t, t_0 + 2\Delta t, \ldots$ for $i$-th node is as follows:

- *Step 1.* Calculate the reference inter-node distances due to current maximal radio range and environment characteristics (for all points of $O^i$).
- *Step 2.* Calculate the values of $\hat{d}_{ab}^{ij}$ for all points of $O^i$ using the formula (1).
- *Step 3.* Calculate the displacement for the whole object $O^i$ (the $i$-th node) for results of *Step 2*.
- *Step 4.* Move the $i$-th node to the new position in the domain.
- *Step 5.* Rotate the $i$-th node (if necessary).
- *Step 6.* Calculate and broadcast to the network the new positions of all points of $O^i$. Return to *Step 1*.

### C. Reference distances calculation

In the first step of our algorithm we have to calculate the reference distances for all points selected from a given node, due to the current maximal radio range, and assumed probability of connection between nodes in a network. To solve this problem we can use $Q$-function defined in [6]. Unfortunately, $Q$-function depends on two parameters: $n$ called "distance-power gradient" that indicates the rate at which a signal strength decreases with a distance, and the signal disturbance $X_\sigma$ that is a zero-mean Gaussian distributed random variable with standard deviation $\sigma$. To estimate both these parameters we apply the commonly used radio signal propagation model that indicates that received signal power decreases with a distance, both in outdoor and indoor environments. Therefore, the power of the signal received by a receiver $P^r$ at a distance $d$ is defined as

$$P^r(d)[dBm] = P^t[dBm] - PL(d)[dB], \tag{3}$$

where $P^t$ denotes power used by a sender to transmit the signal and $PL(d)$ the average signal degradation (path loss) with a distance $d$. A path loss $PL(d)$ is modeled as follows:

$$PL(d)[dB] = PL(d_0)[dB] + 10n log\left(\frac{d}{d_0}\right) + X_\sigma + \sum_i PAF_i \tag{4}$$

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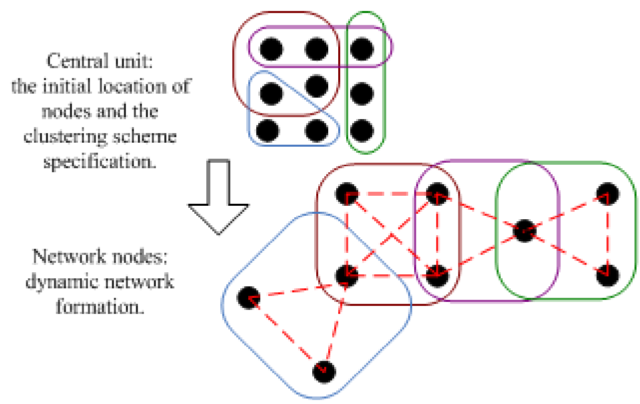


Figure 4. Two steps in formation of a mobile sensor network.

where $d_0$ is a close-in reference distance (for IEEE 802.15.4 usually $d_0$=1m), $PAF_i$ is a partition attenuation factor for $i$-th wall (experimentaly determined).

We calculate $n$ and $X_\sigma$ using formulas (3) and (4), assuming $d = d_c^{ij}$ ($d_c^{ij}$ is a real distance between nodes $i$ and $j$ calculated for known nodes locations) and measured $P^r$. We assume that all nodes are equipped in any location system and are aware of their own location. The detailed description of $n$ and $X_\sigma$ computing can be found in [6].

### D. Self-configured MSN Design

Consider a situation where the task is to create a network that enables the continuous communication with a base station to achieve a given goal or goals. We can form a cluster structured MSN that covers the area between the base station and the cell containing a goal or a set of goals. The cluster formation is based on the following characteristics: 1) all nodes are grouped into overlapping clusters with two, three or four elements, Fig. 4, 2) nodes in a cell must be able to communicate with each other, 3) each cluster can communicate with all neighboring clusters.

The design of a self-configuring network is performed in two steps. We can distinguish two groups of calculation units: the central unit (the base station) and the set of local units – the mobile nodes (see Fig. 4).

*Central unit:* The central unit task is to determine the initial location of nodes and the clustering scheme i.e., the number of cells and the assignment of nodes to clusters. Decomposition of a network into clusters may be predefined or calculated by the dedicated clustering algorithm.

*Network nodes:* Each node sends at time instants $t_0 + \Delta t, t_0 + 2\Delta t, \ldots$ broadcast messages with its location, transmitted signal power $P^t$, cluster (or clusters) identifier ($id$), data about neighbors. We use MAC protocol with beacon synchronization. Next, the node calculates its displacement using the **algorithm 1** presented in Subsection III-B. The calculations are performed based on current distances between nodes and the measured signal power strength. We assume that for reference distances $\bar{d}_{ab}^{ij}$ in the formula (1) the probability of connection between nodes in cluster has to be equal to 99 percent or higher. Finally, the network consisting of calculated clusters is formed. It should be pointed that the value of the reference distance is adaptively modified due to the dynamic changes both in the deployment area and the set of network devices (decreased energy resources).

## IV. Simulation Results

In order to evaluate the performance of our mobility model simulations of various ad hoc network topologies and tasks have been performed. In this paper, we present the example application of our model to support the design of a self-configuring, well-connected network that enables a continuous connection between a goal and a base station.

Consider a situation where the fixed network infrastructure in a disaster area is damaged due to an explosion at a chemical plant. We plan to send several rescue teams to work on the disaster scene (0.36km$^2$). A rescue mission requires that new communication channels be quickly established. MSN can be successfully used to solve this problem. It can enable communications with an adequate quality and can adapt to changing conditions and requirements in the danger zone. In case when we plan a rescue action it is useful to check various possible scenarios taking into account all constraints concerned with the environmental conditions. In presented problem the developed MSN should provide the continuous communication with all rescuers during the rescue action. Simulations were performed in our software platform for parallel ad hoc networks simulation, called MobASim, and described in [9]. The goal of the experiments was to create a network topology with minimal number of nodes that ensures the connection between all rescuers and the base station. We present the simulation of 180 seconds of given ad hoc network operation. The network was composed of 4 rescuers and 10 mobile devices used for re-establishing the communication infrastructure. The mixed outdoor and indoor environment was considered (see Fig. 5).

As a final result of our simulations we have obtained the network consisting of eight clusters with irregular shapes, as presented in Fig. 6. The estimated values of calculated distances $\hat{d}$ between nodes in clusters 0, 1, 5 and 6 calculated at given time instants are presented in Table II.

## V. Summary and Conclusions

In this paper, we have described the novel approach to managing the mobility of a mobile sensor network that combines potential field and particle-based schemes for calculating the mobility patterns. We have defined the suitable artificial potential function for the optimal inter-node distances calculation that captures the task and environment of MSN requirements. In our opinion the proposed mobility model is a good compromise between representativeness

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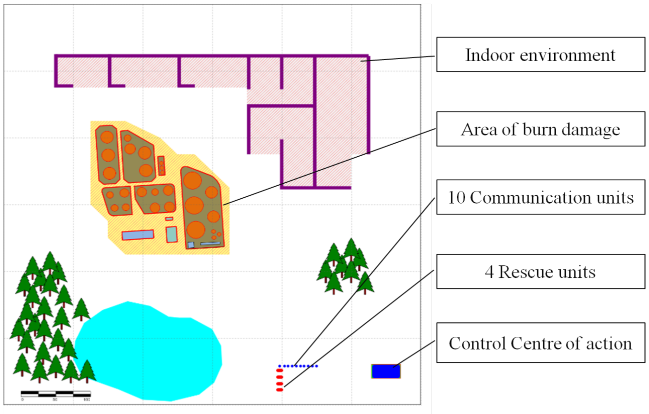


Figure 5. The disaster scene.

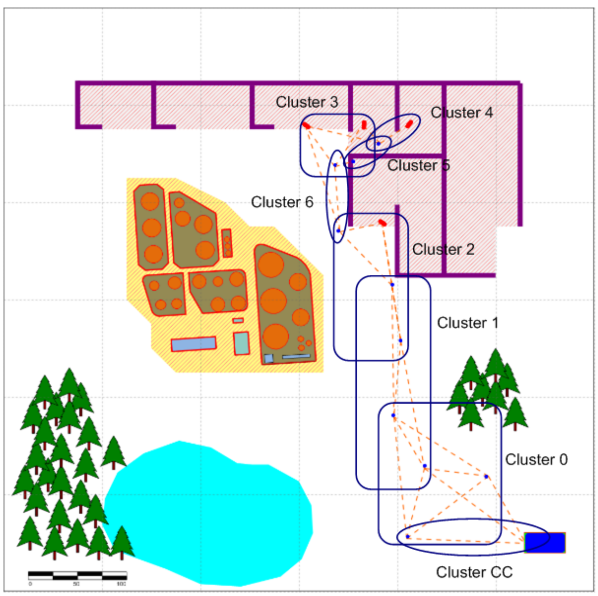


Figure 6. The final topology formed after 180 seconds of wireless devices operation - eight clusters with irregular shapes.

and simplicity. The presented case study showed that by employing a multihop wireless communication and mobile nodes acting as communication relay stations, with movement calculated due to our model even relatively distant points in the deployment area will be able to communicate with the base station. In future research we plan to compare our scheme with other existing models, and test its utility to other ad hoc systems.

Table II
THE TEMPORAL INTERNODE DISTANCES $\hat{d}$ (CLUSTERS: 0, 1, 5, 6).

| Cluster 0 | | Cluster 1 | | Cluster 5 | | Cluster 6 | |
|---|---|---|---|---|---|---|---|
| T[s] | $\hat{d}$[m] | T[s] | $\hat{d}$[m] | T[s] | $\hat{d}$[m] | T[s] | $\hat{d}$[m] |
| 101 | 80.754 | 101 | 82.438 | 101 | 6.608 | 101 | 17.781 |
| 102 | 82.914 | 102 | 83.124 | 102 | 6.688 | 102 | 17.926 |
| 106 | 83.164 | 103 | 84.108 | 103 | 6.999 | 103 | 18.081 |
| 107 | 83.555 | 104 | 85.824 | 105 | 7.284 | 107 | 20.034 |
| 108 | 84.577 | 105 | 86.740 | 106 | 7.629 | 108 | 20.866 |
| 109 | 85.399 | 132 | 87.150 | | | | |
| 110 | 86.674 | 133 | 87.874 | | | | |
| 111 | 87.629 | 139 | 88.175 | | | | |
| 117 | 89.152 | 142 | 89.094 | | | | |
| 118 | 89.747 | 143 | 88.668 | | | | |
| 122 | 90.016 | 144 | 89.094 | | | | |
| 139 | 90.359 | 147 | 88.783 | | | | |
| | | 174 | 89.403 | | | | |

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