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# A MULTI-OBJECTIVE OPTIMIZATION PROBLEMS OF CLUSTERING PROTOCOLS FOR WIRELESS SENSOR NETWORKS USING META-HEURISTIC TECHNIQUES

***Abstract***. *Energy efficiency and prolonging the lifetime is a central issue in wireless sensor network. Clustering methods using meta-heuristic techniques are widely used to address this issue. Besides clustering, meta-heuristic techniques have been also applied to address several other key issues pertaining to WSN such as node deployment, coverage, optimal sensor deployment, topology control, scheduling etc. These problems are formulated as single/multi T objective optimization problems. The overall objectives of the optimization are to minimize energy consumption and maximize the lifetime of the network. The article presents a mathematical formulation of a generic multi-objective optimization problems related to clustering. A generalized model of meta-heuristic based clustering is proposed for its solution, taking into account the features of the WSN. The feature of the model comprises functional multi-purpose clustering quality assessment that takes into account the characteristics of spatial distribution and compactness of sensors, parameters of individual sensors and network characteristics. The article also gives a brief overview of different approaches to clustering methods. A comparative analysis of the improved protocols for heterogeneous WSN has been carried out, which showed the advantages of the proposed solutions.*

***Keywords:*** *heterogeneous wireless sensor network; clustering; meta-heuristic techniques*

## Introduction

Heterogeneous Wireless Sensor Networks (HWSNs) are widely used in applications such as agriculture, health and environment, military tasks, and so on. One of the most important difficulties preventing the wide implementation of the HWSNs is the need to provide energy-efficient data transfer solutions – since such networks can be deployed in remote and inaccessible locations, making it impossible to replace the power supplies of sensors which limits the network operation.

This limitation has led to the use of energy-efficient protocols with cluster topology to increase the battery life (life expectancy) of the network [1-3]

The analysis of power consumption in different modes of operation of wireless sensor networks (WSN) has shown that this indicator is largely determined by data management methods and protocols that are used in data transfer. Among the existing routing protocols, the clustering is the main technique. Cluster analysis is the task of breaking down objects (sensor nodes) into subsets, called clusters, so that each cluster consists of similar objects, and the objects of different clusters differ significantly. It should be noted that clustering methods are widely studied and applied in various domains related to data analysis. However, they cannot be applied directly to WSN clustering for the following reasons: random deployment of sensor nodes in very large quantities, location unawareness, sensory nodes have energy constraints, frequent change in network topology due to degradation of nodes and periodic re-clustering.



Each round of a clustering protocol involves two stages:

(i) cluster formation;

(ii) data transmission.

In the first stage, selections of a cluster head and data aggregation are performed whereas in the second stage data is finally transmitted. Despite the existence of a number of effective clustering solutions, the widespread introduction of heterogeneous WSN faces the complexity of choosing a particular clustering technique. Therefore, the further research in this direction is relevant.

## Analysis of recent research

The literature analysis has shown, clustering improves the life expectancy of the network by two or three times [4], which have, lead the development of a large number of clustering algorithms for WSN.

As it is known the corresponding clustering algorithm and the choice of its parameters (including parameters such as distance function, density threshold, or the number of expected clusters) depend on the particular set of data and the purpose of using the results. Clustering can be formulated as a multi-criteria optimization problem because there are several parameters which need to be optimized for clustering formation such as distance, density of nodes, etc.

Clustering in WSN has the following problems [5]:

– limited memory-sensors have very limited memory, which needs to be taken into account since the cluster centers must receive information from all members of the cluster;

– limited energy – During data transfer, energy consumption is very high which need to be minimized;

– clustering is almost always aimed at improving energy efficiency, but not always paying attention to QoS (quality of service), which determines the probability of receiving a packet from one network point to the other;

– many clustering algorithms do not take into account heterogeneities of the network when there are some advanced sensors that have a larger amount of energy and memory.

These problems should be taken into account when organizing the clustering for HWSNs. We highlight the main direction that have emerged over the past decades in clustering methods for wireless sensor networks, such as probabilistic approach, greedy approach, uneven clustering, fuzzy approach and computational intelligence.

**Different Approaches to Clustering Methods**

**Probabilistic approach to cauterization** In this approach each sensor node is assigned a probability to determine the initial cluster heads (CHs) which also serve as a primary criteria for the nodes to elect themselves as CHs [6]. Other criteria may also be considered such as residual energy for cluster head selection process or proximity to the CH during the cluster formation process in order to reduce energy consumption and prolong the network lifetime.

**Deterministic approach to clustering**. In this method we take into account the specific (deterministic) metric of sensor nodes, such as the identification number of the node (node ID), distance of a CH from a base station, distance of a sensor node from a CH and a base station etc. For selection of a CH. Creating a cluster in this case requires the exchange of a large number of messages from the nodes which will cause loss of energy but such a scheme creates reliable and well-balanced clusters.

**Greedy approach** to clustering (this approach is also called chain based routing). Instead of dynamic clustering, the greedy method is used to form chain of nodes for data transmission [7].

**Unequal cluster approach.** In multi-hop clustering environment, CHs closer to the base station lose their energy faster because of extra inter-cluster traffic at these CHs than the CHs located away from the base station. This kind of situation creates hot spot area or energy hole problem in the network and degrades the performance of the network [8].

**Clustering based on computational intelligence (CI)**. Computing intelligence on the basis of fuzzy logic, neural networks and meta-heuristic techniques is widely applied to solve various complex problems in WSN. Computational intelligence applies several approaches to learning, adaptation, evolution and fuzzy logic to design systems with some intelligence. In this work we apply meta-heuristic based clustering techniques [9].

**Clustering based on fuzzy logic**. Fuzzy logic models the way humane thinks. It measures uncertainty, which is expressed through some linguistic variables such as “majority”, “many”, “often”, “rarely”, etc. It is widely used in applications where there is uncertainty. In addition, it facilitates the formation of a cluster based on overlapping metrics which can work better than a single metric [10].

**Meta-heuristic methods** are used to solve complex optimization problems (for example, NP-complete problems or global optimization problems) [11-12]. NP-complete problem are a type of a problem that does not have known solutions for polynomial time. Unlike heuristic methods that are intended to solve a particular problem, meta-heuristic methods are more generalized and can be applied to a wide range of problems. Examples of such algorithms are: genetic algorithms [13-14], biogeography optimization [15-16], swarm optimization algorithms [17] etc.

The following advantages are inherent in meta-heuristic methods: robustness; relative simplicity of implementation; good scalability due to parallelization; flexibility; availability of a large number of software for their implementation; possibility of effective solution of NP-complete tasks; possibility of application for problems of multi-objective optimization, especially in the case of complex and non-smooth objective functions. But there are also disadvantages of meta-heuristic methods such as: the lack of guarantees of finding the optimal solution; the need to determine the fitness function and adjust a number of parameters.

**Purpose of the article**

Taking into account the main trends in clustering tools and lists the advantages and disadvantages of a meta-heuristic approach, we can conclude that, in the framework of the study, improvement of clustering approaches for heterogeneous WSN (HWSN) protocols based on met heuristic strategies. The purpose of the article is to develop a generalized meta-heuristic clustering model for wireless sensor network routing protocols.

The task of clusterization in heterogeneous WSN.

Let's formulate the problem of clusterization in heterogeneous BSM.

Let $\mathbf{C} = (c_1, c_2, \dots, c_N)$ be a set of sensors ($c_i$ is a sensor node characterized by a vector of parameters $(z_i)$); $CH_i$ is a set of cluster heads.

Then, the clustering algorithm for heterogeneous WSNs is a function f: $\mathbf{C} \rightarrow \mathbf{CH}$ that randomly assigns a cluster head from the set $CH_i$ to the arbitrary sensor node from the set of $CH_i$ in accordance with the selected optimization function, that is, clusterization can be considered as the problem of optimal splitting of the sensor set in K-groups.

Thus, on the one hand, according to the partition into clusters, the set C can be represented by the expression:

$$\mathbf{C} = (\mathbf{C}_1, \mathbf{C}_{2, \dots,} \mathbf{C}_K),$$

where: $\mathbf{C}_i$ represents itch cluster centroids.

On the other hand, taking into account the functions performed by sensor nodes and the corresponding requirements by them, the set C can be represented as

$$\mathbf{C} = (\mathbf{C}^{(о)}, \mathbf{C}^{(м)}, \mathbf{C}^{(к)}),$$

where: $\mathbf{C}^{(о)}$is the set of network elements that perform the functions of receiving data from sensors and transmitting them to the network (energy requirements are lowered);

$\mathbf{C}^{(м)}$ – the main nodes of clusters $CH_i$ (routers) – cluster elements that execute in the data relay function;

$\mathbf{C}^{(к)}$ – element of the network - the base station (gateway), performs the function of providing communication with the high-speed interface.

Thus, due to the various functions of the network elements and the heterogeneity of their characteristics in heterogeneous WSN it is essential to take into account the parameters of the HWSN and individual sensor nodes.

It should be noted that HWSN is characterized by a large number of parameters, constraints and requirements for their functioning [5]:

– input parameters (in different combinations): the frequency at which the data transmission is carried out, the power of such transmission, the residual energy of the nodes, the availability and possibility of additional charging of local power sources, sensitivity range of sensors, required communication range, location and / or mode sensor operation, sensor positioning density, data sampling frequency, packet length, possibility of moving destination;

– limitations (in different combinations): the ability to connect to the network if necessary, the level of interference, the energy and distance of data transmission, the features of coverage, network topology, its spatial density, cost, signal lag, network reliability;

– output parameters (in different combinations): optimum location and / or number of sensors, optimal transmission power, optimal coverage, optimal bandwidth, optimal delay, optimum cost, optimal packet error rate during data transfer, reliability.

The objectives of the HWSN can also be different (in different combinations): to achieve maximum energy efficiency, to achieve maximum channel quality, increased lifetime of the network, reliability, maximum spectrum use, coverage, minimum delay, cost, the required level of interference and packet error rates.

Thus, we can conclude that WSNs may require both a large number of output parameters and the fulfillments of contradictory goals. This affects the overall clustering design approaches in WSN. Most of the clustering approaches consider the following characteristics.

**1. Spatial characteristics** (taking into account the hypothesis of the proportional dependence of the distance between nodes and the energy expended on receiving-transmission) [5].

The main indicators are:

$\boldsymbol{D_{intra}}$ – intra-cluster distance which is also called compactness (spatial variance relative to the center of the cluster);

$\boldsymbol{D_{inter}}$ – inter-cluster distance which is also called seperation (distance between different clusters).

Thus, in the general form, the target function for the search for the extremum of spatial indicators takes the form:

$$Q_1(\overline{w}, \overline{c}) = f(D_{intra}, D_{inter}) \rightarrow max, \quad (1)$$

where: $\overline{w}$ – Random distribution;

$\overline{\mathbf{c}}$ – spatial parameters of WSN ;

$\overline{w}$ – is determined by the finite number of sensors (by random sample size) and tend to zero. In this case, the following quality criterion is used

$$J(\overline{c}) = \lim_{k \to \infty} [Q(\overline{w}, \overline{c})] = M\{Q(\overline{w}, \overline{c})\}.$$

The compactness of the cluster in the spatial domain is estimated by the dispersion characteristic and is determined by the applied metric in the attribute space.

Example:

$$D_{intra} = \sum_{i=1}^{CH_k} \sum_{\forall CH_i \in C_i} d(C_j, CH_i),$$

– measures compactness within a cluster;

$$D_{inter} = \sum_{\forall CH_i, CH_j, CH_i \neq CH_j} [d(CH_i, CH_j)],$$

– measures Separation between clusters.

**2. Wireless sensor networks** parameters are determined by the type of coverage, topology, location, etc.

It is shown that when organizing data transfer operation in heterogeneous WSN based on cluster topology, it is necessary to consider not only spatial characteristics, but also network parameters:

$$Q_2(\bar{w}, \bar{e}) \rightarrow max \qquad (2)$$

where: $\bar{e}$ – vector parameter of WSN.

**3. Sensor parameters**

It is noted that the influence on the quality of data exchange in heterogeneous BSM is carried out and parameters of sensors.

Such parameters can be the residual energy of the sensor and the amount of memory, the average speed of processing information, etc. [5].

$$Q_3(\bar{w}, \bar{z}) \rightarrow max. \qquad (3)$$

The method of cauterization based solely on spatial indices gives a satisfactory result in the case of homogeneous WSN.

However, the analysis of heterogeneous WSN showed that the energy consumption of WSN also depends on the following basic parameters:

$$\bar{z} = \{z_1, z_2, z_3, z_4\},$$

where: $z_1$ – residual energy of sensors ;
$z_2$ – data processing speed x;
$z_3$ – the amount of memory;
$z_4$ – Physical nature of the sensors, etc.

Taking into account (1-3) for estimating the quality of clustering of heterogeneous wireless sensor networks, a generalization function is proposed

$$\bar{Q} = \{\alpha_1 Q_1, \alpha_2 Q_2, \alpha_3 Q_3\}. \qquad (4)$$

Studies have shown that the functional (4) has many extremes with significant random disturbances, which are determined by the number and nature of the sensors, the conditions for radio waves, three-dimensional topology of the terrain, and so on.

Therefore, the result of optimization essentially depends on the starting point of finding the optimal solution, on the level of random perturbations, on the method of estimating the direction of search, on the obstacles that operate in the wireless channel, and so on.

An analysis of existing multi-purpose optimization methods has shown that for solving problems that are based on the search for the extremum of target functions with many extremums, it is essential to use meta-heuristic strategies that successfully solve such problems. Such an approach can be considered particularly relevant in case of violation of the regularity of fitness function.

However, the choice of a particular meta-heuristic method depends on the type of specific functional quality and requires additional research.

Therefore, in this article a generalized model of meta-heuristic optimization was developed, which takes into account both the features of meta-strategy strategies and the features of heterogeneous WSN.

**A generalized model of meta-evolutionary clusterization**

The analysis showed that, despite the fact that outwardly meta-strategy strategies vary widely, they can all be described by a similar rule. A generalized model of meta-evolutionary clusterization based on the following optimization function is proposed, taking into account the spatial and energy characteristics of heterogeneous WSN:

$$x_{t+1} = \mathbf{A}\,(x_0, x_t, \mathbf{p}(t), \bar{Q}), \qquad (5)$$

where: **A** – some mapping function;
$x_0$ – estimation of the initial population;
$x_t$ – solution at stage t;
**p**(t) – parameters that depend on the chosen strategy, which in general depend on the results of the previous steps of the algorithm 1, ... t-1;
$\bar{Q}$ – fitness function (optimization function) (4).

It should be noted that the main disadvantage of meta-heuristic methods is the dependence of the results on the selection of the initial population. Randomness initialization of the initial population, as a rule, does not take into account the initial topology of sensor nodes and does not ensure the convergence of the algorithm. In order to eliminate this disadvantage, it is suggested to take into account the characteristics of the spatial location of sensor nodes by preliminary estimating the position of the main nodes of the clusters by means of preliminary clusterization using the k-mean method in accordance with (5).

The method of combined meta-evolutionary clustering for heterogeneous BSM communication protocols based on model (5) is proposed, which combines the advantages of meta-strategy optimization strategy and the k-medium method, which consists of the following steps.

*Step 1.* Initial parameters are set: the maximum number of rounds Rmax, the initial number of clusters K.

*Step 2.* The initial population is determined. To initialize the initial population of the selected meta-strategy, it is proposed to take into account the spatial arrangement of the sensors, and to conduct a preliminary clusterization using the k-medium algorithm.

Let heterogeneous WSN C contain N sensor nodes {c1, c2, ..., cN}, which need to be grouped into K clusters that do not intersect one another(non-overlapping clusters), that is.

$C = \{C_1, C_2, ..., C_K\}$, such that

$C_i \neq \varnothing$ for all i,

$C_i \cap C_j = \varnothing$ if $i \neq j$ and $C_1 \cup C_2 \cup \ldots \cup C_K = C$.

Then perform the following tasks:

a) Select randomly k cluster centroids: $C_1, C_2, ..., C_{K;}$

b) Given N sensor nodes($c1, c2 \cdots cN$, $i = 1 ... N$), which need to be included into clusters $C_j$ ($Cj$, j $\in \{1,2, \ldots K\}$), in such a way that $\|c_i - C_j\| < \|x_i - C_p\|$, p = 1,2…K and $j \neq p$ , calculate new cluster head nodes

$C_1^*, C_2^*, .., C_K^*$ as:

$$C_i^* = C_i^* = \frac{1}{n_i} \sum_{x_j \in C_j} x_j \qquad i = 1, 2,..K ,$$

where: $n_i$ is the number of elements(nodes) belonging to a cluster $C_i$;

c) if $C_i^* = C_i \forall$ i =1,2 …K, then terminate, otherwise go to b).

*Step 3.* Clustering results are refined using the chosen meta-heuristic strategy and the choice of the main node CH of each cluster in each round.

The realization of this method allowed, on the basis of a generalized meta-optimization model, to develop a family of meta-heuristic methods of clusterization (based on a genetic algorithm, on the basis of a particle swarm optimization algorithm and on the basis of biogeograph based optimization algorithm), and used them to improve the clustering protocols of heterogeneous wireless sensor networks. The choice of the selection of parameters of equation (5) depends on the features of the application of heterogeneous WSN.

**Check the effectiveness of the proposed model**

Since WSN clustering protocols work in two stages: (i) clustering, choosing the main node of the CH cluster, forming a cluster, and aggregating data and (ii) transfer of data, it is proposed to evaluate the effectiveness of the proposed solutions by plotting a protocol based on various meta-heuristic methods. At the first stage, in order to improve the protocols, it is proposed to use the developed methods of combined meta-evolutionary clusterization on the basis of the genetic algorithm (KGA, KGACVI), on the basis of the swarm optimization algorithm (KPSO) and on the basis of biogeography (KBBO) [13-17].

Verification of the efficiency of advanced routing protocols was carried out at the following stages:

*Stage 1.* Simulation of the network.

*Stage 2.* Combined meta-evolutionary clustering. The main nodes of clusters CH are determined.

*Stage 3.* Data transmission between the elements of the corresponding BCM cluster and the main node of the cluster CHs.

*Stage 4.* The obtained statistical data obtained during testing of improved communication protocols and existing ones are summarized in the table.

*Stage 5.* An analysis, synthesis of the obtained results and conclusions about the expediency of using improved communication protocols based on combined meta-clusterization methods based on the genetic and onion algorithm and on the basis of the biogeography model are made.

To evaluate the effectiveness of the classical modern and improved with the proposed algorithms of communication protocols of heterogeneous wireless sensor networks, the following metrics were used [13-17].

Network Lifetime (Network Lifetime) - this is the time from the start of the network to a certain point. As a rule, the lifetime of a network is defined as the number of rounds, when all nodes exhaust their energy and “die”.

Stability Period – Defines the time interval from the start of the network (first round) until the first node does not exhaust its energy.

Residual Energy – the residual energy of the network in each round is calculated by subtracting the energy consumed by nodes from the total energy per round.

Throughput – the indicator of the number of packets received by the base station from the cluster head (CHs) and which it can process over a certain period of time.

According to the results of modeling and practical implementation of developed energy-efficient protocols using combined meta-evolutionary clustering methods, it has been established that with significant heterogeneity of WSN (up to 20 %). The main indicators of energy efficiency of the network became better: life expectancy – on average up to 5 times the residual energy taking into account the energy characteristics of the sensors and the network – by several orders of magnitude, the stability period – an average of 2 times, the throughput – an average of 2,5 times [13-17].

**Conclusions**

The article presented a mathematical formulation of a generic multi-objective optimization problems related to clustering. A generalized model of meta-heuristic based clustering is proposed for its solution, taking into account the features of the WSN.

The feature of the model is that it contains a functional multi-purpose clustering quality assessment that takes into account the spatial characteristics of sensor nodes, that is, the characteristics of spatial distribution and compactness of sensors, parameters of individual sensors and network characteristics. This allowed taking into account not only the unpredictable topological changes of the BSM but the change in the energy of the main nodes of the clusters and individual sensors.

The proposed model will allow one clustering procedure to be simulated on a single methodological basis on the basis of different meta-heuristic algorithms, it is reasonable to choose their parameters. The article also presented a brief overview of different approaches to clustering design.

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## ЗАДАЧА БАГАТОЦІЛЬОВОЇ ОПТИМІЗАЦІЇ КЛАСТЕРНИХ ПРОТОКОЛІВ ДЛЯ БЕЗДРОТОВИХ МЕРЕЖ З ВИКОРИСТАННЯМ МЕТАЕВРИСТИЧНИХ МЕТОДІВ

***Анотація.*** *Енергоефективність та підвищення терміну експлуатації є основною проблемою бездротових сенсорних мереж (БСМ). Методи кластеризації з використанням мета-евристичних методів широко використовуються для вирішення цієї проблеми. Метаевристичні методи також використовуються для вирішення декількох інших задач, що стосуються БСМ, таких як раціональне розгортання вузлів, забезпечення покриття, оптимальне розгортання датчиків, керування топологією, планування тощо. Загальними цілями оптимізації є мінімізація споживання енергії та максимізація терміну експлуатації мережі. У статті сформульована проблема багатоцільової оптимізації, яка пов'язана з кластеризацією. Для її розв'язання пропонується узагальнена модель мета-евристичної кластеризації з урахуванням особливостей БСМ. Особливістю моделі є багатоцільова оцінка якості кластеризації, яка враховує характеристики просторового розкиду та компактності кластерів, параметри сенсорів та мережеві характеристики. У статті також дається короткий огляд різних підходів до методів кластеризації. Проведено порівняльний аналіз удосконалених протоколів гетерогенних БСМ, який показав переваги запропонованих рішень.*

***Ключові слова:*** *бездротова сенсорна мережа; кластеризація; протоколи маршрутізації*

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## ЗАДАЧА МНОГОЦЕЛЕВОЙ ОПТИМИЗАЦИИ КЛАСТЕРНЫХ ПРОТОКОЛОВ ДЛЯ БЕСПРОВОДНЫХ СЕТЕЙ С ИСПОЛЬЗОВАНИЕМ МЕТА ЭВРИСТИЧЕСКИХ МЕТОДОВ

***Аннотация.*** *Энергоэффективность и повышения срока эксплуатации является основной проблемой беспроводных сенсорных сетей (БСС). Методы кластеризации с использованием мета-эвристических методов широко используются для решения этой проблемы. Метаэвристические методы также используются для решения нескольких других задач, касающихся БСС, таких как рациональное развертывание узлов, обеспечение покрытия, оптимальное развертывание датчиков, управление топологией, планирование и т.п. Общими целями оптимизации является минимизация потребления энергии и максимизация срока эксплуатации сети. В статье сформулирована проблема многоцелевой оптимизации, связанные с кластеризацией. Для ее решения предлагается обобщенная модель метаэвристической кластеризации с учетом особенностей БСМ. Особенностью модели является многоцелевая оценка качества кластеризации, которая учитывает характеристики пространственного разброса и компактности кластеров, параметры сенсоров и сетевые характеристики. В статье также дается краткий обзор различных подходов к методам кластеризации. Проведен сравнительный анализ усовершенствованных протоколов гетерогенных БСМ, который показал преимущества предлагаемых решений.*

***Ключевые слова:*** *беспроводная сенсорная сеть; кластеризация; протокол маршрутизации*