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A Review on the Implementation of Multiobjective Algorithms in Wireless Sensor Network

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Abstract: Wireless sensor networks have various contradictory requirements like other types of networks. Network lifetime, cost, coverage, connectivity and delivery latency are the major requirements in these networks. Along with these requirements, limited computational and power resources and low communication capabilities are also hardening the problem to be solved. One of the ways of providing the required parameters for WSNs is exploiting the deployment methods. In this paper different Multi-Objective Evolutionary Algorithms and their usage for optimizing WSN deployment are investigated and a review of existing solutions is presented. Besides, various objectives are considered and the optimization problem formulation is studied. Lastly, existing simulation environments used for evaluating such solutions are discussed.

Key words: WSN % MOEA % Coverage % Connectivity % Deployment % Lifetime % Latency

INTRODUCTION

Whenever a large number of tiny devices that have limited resources such as CPU, storage, battery power, communication range and bandwidth named as sensors come together to form a network, a Wireless Sensor Network is born. Various environmental phenomena can be sensed by these sensors and they can process the data in the network and communicate to other nodes of the network including both sensors and sink (data gathering) nodes using their wireless communication capabilities. This communication is usually done using multihop communications. Potentially a WSN can be deployed over a wide area covering many kilometres with edge nodes that are many kilometres distant from each other. Because of limitations in sensor nodes' energy resources and need for a great amount of energy to transmit data over long hops, multi-hopping is used in almost all WSN applications to increase network lifetime. Besides, using multi-hopping, gives the network the opportunity to reduce radio interference and extend overall network bandwidth. Many applications dealing with surveillance, monitoring and control can be handled using WSNs.

Wireless Sensor Networks (WSNs) are one of the most significant technologies of the new decade. Cheap and tiny sensors can be deployed as a network using the advances in the wireless communication technologies and Micro Electro-Mechanical Systems (MEMS). In addition, being connected to the Internet provides new applications that never had happened before like security surveillance, monitoring the environment and controlling industrial process. Severe storage, computation and energy constraints combined with higher deployment dense and unreliability are unique characteristics of WSNs that distinguish them from cellular systems and MANETs. These characteristics arises new challenges in developing WSNs. The large amount of research from both academic and industrial resources on the WSNs has led to various solutions and applications. The foresight of the near future is wide usage of WSNs in different fields which will forcefully change our way of life. Recently it is shown that Multi-Objective Evolutionary Algorithms (MOEA) is a strong enough tool to deal with unconstraint real life problems such as WSN deployment [1].

The rest of this paper is organized as follows: in Section 2, a brief description of WSN optimization parameters is presented. In Section 3, fundamentals of Multi Objective Optimization are discussed. In the following section, existing solutions for WSN deployment using MOEA are discussed. In Section 5, the simulation environments for existing solutions are presented and a comparison of their results is illustrated. Finally, in Section 6, we draw the main conclusions.

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WSN Parameters: Every wireless sensor network has properties that can be measured to evaluate the whole network according to the methods and protocols employed in it. There are six significant parameters including coverage, connectivity, scalability, lifetime, latency and cost. These parameters are rarely used all together and usually are used as a combination of them or even one of them.

Coverage: Most of the coverage problems in WSNs are related to the quality of monitoring the area or tracking the events. Because of limitations in the sensing range of sensor nodes, a proper sensing task is achieved by an appropriate node deployment and gain of the requested coverage level. The Art Gallery Problem is defining the number of observers in an art gallery to observe the entire gallery. Mapping the same situation onto sensor networks, a sensor node is just like an observer and the sensing area should be covered like an art gallery. This problem is proved to be solved optimally in 2D environments while it has been proved that the problem becomes NP-hard when it is generalized to 3D environments [2].

When the nodes are deployed randomly (i.e. scattered from and airplane) the position of the nodes is out of control and as a result some places in the target region remain uncovered that are known as coverage holes. In some other solutions, sensor nodes are mobilized to cover the coverage holes.

The ratio of the area covered by sensor nodes to the entire application area is defined as coverage. The ideal value for this parameter is 100% which means the whole area is covered by the sensor nodes. Besides, coverage degree for a point in the area is defined as the number of sensor nodes covering that point. Based on this definition, the coverage degree on a wireless sensor network is defined as the minimum of coverage degree for the environment. Sometimes the coverage degree of specific regions of the area is more than the requested coverage degree, which leads to the use of scheduling algorithms to reduce power consumption in the network.

A simple way of measuring the coverage is dividing the target field into a grid of small squares where each of them is representing a sensible area. Any of them containing a sensor node is considered covered otherwise uncovered. Using this measurement method, the percentage of covered squares to all of the squares is known as the amount of coverage. Researchers of [3] have considered this model to measure sensing coverage for their approach.

The most common definition for sensing coverage in WSNs is the circular model. This definition is also known as binary disc where every point inside the coverage disc centred on the sensor node is covered and any point out of it is uncovered. Because of the characteristics of the real world, this model was not realistic and researchers have proposed a more realistic model based on probability. Depending on the sensing technology used by a sensor node, a variation of this sensing model is issued which is applicable to networks with sensing characteristics similar to radio waves.

According to these models used to represent each node's sensing capabilities, sensing coverage for the entire network can be determined. To the best of author's knowledge, the only applied sensing coverage measurement models for WSNs are grid and circular models. Probabilistic circular model is more realistic model but is rarely used because of its complexity [4].

Connectivity: Transferring sensed data from a sensor node to a decision making centre or within the network to make the decision, depends on the ability of nodes to communicate with each other. Using a radio signal transceiver as the communication device of sensor nodes leads to the communication models to inherit the characteristics of radio signals. Initially binary disc was used for modelling the communication between two sensor nodes. Because of simplicity, the model is still in use by many researchers in the area. The Euclidean distance between two sensor nodes is used to determine connectivity between nodes. Complexity of radio waves' behaviour has led to other communication models which are more complex and time consuming in computations which are taking other influencing parameters like interference into account.

Independent to the communication model utilized in the network modelling, network connectivity is measured by network connectivity graph. If the network connectivity graph is connected as a whole graph, the network is assumed connected, otherwise partitioned. If there is more than one distinct path between every two sensor nodes of the network, connectivity degree is defined as the minimum number of these paths.

Scalability: Some WSN applications need the order of deployed sensor nodes for monitoring and detecting events in the target environments to be as high as hundreds or thousands. In some specific applications this number may even reach an extreme value of millions. Any new scheme in the wireless sensor networking must be applicable to such large values. The new scheme should grow or develop without major changes to the initial design [5].

Lifetime: Some of the researchers have measured the overall network lifetime by total number of live nodes. Some others use the number of nodes already connected to the sink node. In the work by [6], network lifetime is measured using both *Time for last node to die* and *Time to network partition* which is when the first nodes runs out of energy and becomes non-operational and makes the network to be partitioned [6].

Network lifetime is directly related to the battery lifetime of the sensor nodes. The increase in node's activities leads to a network node's power consumption that results in lower battery and less network lifetime. There are different approaches to increase the network lifetime. One major approach is to balance activities among nodes to reduce the risk of one node's failure [6]. In the work by [7] the concept of proxy forwarders and intermediate forwarders are used to increase the network lifetime. On the other hand, researchers of [8] have assumed that resource rich mobile nodes are moving around the area and operate instead of low-energy nodes to extend network lifetime.

Latency: The delay in transmitting data, data aggregation and routing is defined as latency. This parameter can be measured as the time between arrival of data packets at the destination and its departure from the source node [9]. Using alternate paths has potentially longer latency in comparison to the primary path between two nodes and accordingly more energy usage. Some approaches are doing data fusion to decrease network traffic which in turn introduces latency in the network [10].

Cost: The cost of a wireless sensor network starts from the construction phase of sensor nodes. Depending on the application and sensor devices used in the node, the cost of the node can be variable. Other equipments which come with some types of sensor nodes like GPS can also affect the final cost of the node. Some applications do not consider node cost because of the low price of nodes used. In these cases, random deployment is a good way to deploy nodes in the target area. A forest, an ocean, or a battle field are some examples of such targets. In some others, the node costs are high enough to be included in the node deployment strategies.

Along with the node cost, deployment and maintenance fees are also applied to the total cost of a network. When the deployment choice is not random and it is done by hand or automated using specific robots, it should be taken into account. Node count is as an overall metric to measure all of these parameters together under the network cost. The more sensor nodes a network needs, the more its construction, deployment and finally maintenance fees will be.

Multi-Objective Optimization Fundamentals: Most of the applications in real world depend on more than one objective function. The only solution for optimizing these applications is optimization of these objectives functions simultaneously and in a systematic way. This process is called *vector optimization* or *multiobjective optimization (MOO)*.

In its general form, a MOO is posed as following:

$$\underset{x}{Minimize}\, F(x) = \left[F_1(x),...,F_k(x)^T \right] \qquad (1)$$

Subject to $g_i(x)\#0, j=1,2,...,m$

$$h_l(x)=0, l=1,2,...,e$$

where there are *k* objective functions, *e* equality constraints and *m* inequality constraints.

Having the n as the number of independent variables x_i, $x0\ E^n$ is the vector of *decision variables*. F(x) is the vector of objective functions $F_i(x){:}E^n 6 E^1$. These functions are also called *criteria* or *objectives* in brief. The *Minimize* criterion is not violating the general form of the problem and depending on the application, the criterion can be simply *Maximize*.

Economic *equilibrium* and *welfare theories*, pure mathematics and *game theory* were the main origin of MOO [11]. The history of MOO and further discussion around it is done in [11]. According to the traditional interpretation of game theory, any situation of cooperation or conflict between any numbers of players more than one having possibility for multiple moves or strategies is a game. A MOO with its decision makers controlling certain design variables is represented by game theory. The result of players' cooperation is the same as a single decision maker for a MOO problem.

While other classifications do exist, the multiobjective approaches are mainly classified into *vector optimization* and *scalarization* methods. Having objective functions in form of a vector, the elements of the vector can be combined to form single scalar objective function which is scalarizaiton. Not all of the researchers distinguish between these two classes; vector optimization loosely implies independent treatment of each objective function. In this study, we will discuss them both.

Unlike optimizations for single-objective functions, a solution for a MOO is more of a concept than a definition. In these types of problems there is no single solution and most of the time a set of points that fit a predetermined optimum definition is necessarily determined. This predetermined concept is known as Pareto optimality. According to the definition, a point $x \in X$ is Pareto optimal if there is no other point $x \in X$, such that $F(x) \leq F(x^*)$ and $F_i(x) \leq F_i(x^*)$ for at least one function.

MOEAs for WSNs: The nature of WSN applications has led to complexity of algorithms exploited in their design. The main existing solutions for WSNs which have employed MOEAs are presented in the following according to the base algorithm they have used for optimization:

GA Based: As a leading and among the first researches on exploiting MOEA for solving WSN deployment problem the authors of [12] have considered the sensor coverage and the network lifetime as their competing objectives. According to their findings, different relations between the sensing and the communication range, as a discriminating parameter, results in two basically different types of layouts. One type is packing the nodes together and the other one is organising the nodes in a hub-and-spoke way. It is assumed in the work that the nodes are placed in an automated way. The network is homogenous and binary circle modelling is used for sensing and communication. The resulting Pareto-Optimal designs will have both coverage and lifetime maximized. In practice, the optimal result for the network layout varies according to the ratio between R_c and R_s that is much different in example for seismic and acoustic sensor nodes. Their results shown that for a relation between R_c and R_s below 1/2, the structure resembles like beehive and for the ratios above this the design is more similar to hub-and-spoke.

Multiobjective optimization based on GA which is mostly known as Non-dominated Sorting Genetic Algorithm is used in [1] to solve the *k*-connected deployment and power assignment problem known as deployment and power assignment problem (DPAP). The research is covering WSN benefiting from a limited number of expensive nodes that have a reconfigurable transmission power. The result of running the algorithm is the layout of the wireless sensor network. The communication and sensing models utilized in this work are the simple relevant path loss model and binary disk model respectively. The authors of this work have defined and formulated the problem in terms of the design of several constraint techniques to tackle the problem. A penalty function (PenF) is defined for directing the search for Pareto Optimum results into the feasible regions of the search space. The repair heuristic which is designed specifically for this type of problem is used for transforming an infeasible solution to a feasible one while maintains the efficiency of MOEA/D at the same time. The authors of this work also have adopted the rules of the superiority of feasible solutions to handle the constraints with the popular NSGA-II [13] that prefer the feasible solutions over the infeasible solutions. The simulation results of [1] has shown that providing a solution for wireless sensor networks needs to adopt the original solutions using the WSN-knowledge.

Maximizing the lifetime of the network is the main objective in [14]. In this algorithm, the energy data for all of the individuals of the generation are calculated once the WSN does not keep the minimum requirements for coverage and connectivity. On the other hand, the algorithm searches for an individual who is able to increase the lifetime of the network while the coverage level is kept and the active nodes are connected to the sink node. Using the results from the execution of this algorithm prior to the deployment, each node will be able to decide when it must be activated and how it will be connected to the network.

Some of the points of a target area in a WSN may require different level of importance due to their geographic relation to the events. These types of WSNs with non-uniform area of interest are studied in [4] and a solution is proposed to provide a deployment strategy that increases the network lifetime and provides desired coverage. Probabilistic coverage and shadowing fading link are two modelling methods used to provide the solution. The nodes of the problem are static and after deploying the nodes there will be no change in their position. NSGA-II is used to provide the solution for a relatively small number of nodes. Running of the algorithm to provide the solution for relatively big areas of interest take a long time to converge and produce the result. If there is a change in the requested coverage for a sub-area after providing the layout, the solution is able to run just for that sub-area while global optimization is provided.

A hybrid approach is proposed in [15] to solve the problem of selecting the largest number of disjoint sets of sensors which completely covers the target area. A forward encoding scheme for chromosomes is used in the approach and some effective sensor schedule and genetic transition operations are employed. Their novel forward encoding scheme is consistently increasing the maximum gen value of each chromosome with the solution quality representing the number of disjoint sets. Considering the R_c of nodes at least twice of R_s, the research has only considered the coverage problem. The research is trying to increase the network lifetime by exploiting an enhanced GA algorithm. Schedule Transition Hybrid Genetic Algorithm can solve both area-coverage and point-coverage problems. Binary disk is used to model sensing coverage of the node.

Once a sensor node failure occurs as a common phenomenon in a densely deployed WSN, there is no fixing or replacement to the node. On the other hand the networks are designed in a way to cover such failures and keep the network connected while covering the area. In [16] the aim is to redesign the whole network upon the failure of a node using a local on line algorithm. Along with providing network connectivity and coverage the solution is trying to minimize energy consumption of the network which leads to prolonging network lifetime. The Multiobjective On line Hybrid Algorithm (MultiOnHa) [16] is proven to be efficient for solving the dynamic coverage and connectivity problem in flat networks. The approach is composed of a Multiobjective Global on Demand Algorithm that is exploiting NSGA-II to solve the so called DCCP problem and a Local online Algorithm (LoA) that is benefiting from some deterministic rules to restore network coverage in a fast way. Whenever the number of new active nodes is less than a predefined threshold, the approach is using the local algorithm to solve the problem while the solution provided after high number of new active nodes becomes rough.

The problem of having limited energy resources is a basic obstacle to tackle with in WSNs. Radio transmission is one of the energy consuming duties of a network node. Adjustable transmission power has become a practical case these days and it has become possible to control the communication range of a node to reduce energy consumption. This development in the technology has become a point of start for algorithms which try to minimize energy consumption of network nodes by tuning the communication ranges of the nodes to be in the optimum configuration. The approach in [17] is a Generalized Subproblem-dependent Heuristic (GSH) which is hybridized with MOEA/D to tackle the problem of densely deploying nodes in a target area and assigning power to them. The sensing model used in this model is binary disk model to have the coverage problem computationally manageable using consecutive grids. The solution decomposes the dense deployment and power assignment problem (d-DPAP) into scalar subproblems and discusses based on their objective preference and then GSH is applied. The simulation results of this work have shown that hybridization of the proposed GSH with the MOEA/D generates better results than the general MOEA/D and the popular NSGA-II. In most of the applications for WSNs guaranteeing the provided coverage and connectivity is very important. The failure of the sensor nodes which is caused either by having the battery discharged or by external damages could lead to coverage holes or network fragmentation. In such conditions having redundant nodes which provide the route to the sink node or monitor the area is a solution. The maximum number of failing nodes which allows the network to function properly is known as the fault tolerance degree of network. The authors of [18] have extended their solution in [17] to provide the network with a guaranteed connectivity known as *k-connectivity*.

PSO Based: In the work presented in [19] Particle Swarm Optimization algorithm [20] is used to dynamically restructure the network to achieve a uniformly distributed connected network instructing by data processing unit. The nodes of this network are homogenous and there is a high energy communication node. The energy consumption model of the nodes follows a per message scheme. The goal is having a covered target area and an energy efficient layout. According to the results of the conducted simulations, binary disk model gives a better coverage than stochastic sensor model which not practical. While the target area is usually divided into sub-regions for easy layout organization and management, the size of sub-regions is important for having an accepted stochastic sensor model.

Simulation Environments: The simulation of WSNs in case of using multiobjective algorithms is composed of two different stages. In the first stages, the algorithms are run simulating the behaviour of nodes and the results are optimized until achieving convergence. In the second stage the results are fed into a network simulator to check the resulting solution. In most of the cases MatLab is chosen to pass the first stage. The latter stage benefits from various existing simulation environments including but are not limited to NS-2, JSim, OMNET++, NesCT, PAWiS, GlomoSim, OPNET, Ptolemy II, Cell_DEVS, GTNetS, SystemC, Prowler, NCTUns6.0, JiST/SWANS and SSFNet.

NS-2: NS-2 is an object-oriented network simulator which is written in C++ and its origin is Unix based operating systems. It is the most widely used simulator for general purpose networks and WSNs. Although the main platform for using NS-2 is Unix based operating systems, but using Cygwin it can be used on MS. Windows family operating systems too.

Jsim: JSim is a simulation environment to build quantitative numeric models and analyzing them. Once it is based on Java, the simulator is able to run under Windows, Macintosh and Linux, or even within a browser as an applet.

OMNET++ and its Subcategories: An extensible simulation library and framework which is providing an infrastructure for building network simulators. The open-source simulator which can be installed on Linux, MS Windows and Macintosh has extensions for several functions including real-time simulation, alternative programming languages (Java, C#), network emulation, SystemC integration and database integration.

NesCT is a programming language translator that gets program code in NesC and produces C++ classes for OMNET++. It is available on both Linux and Windows installations of OMNET++.

PAWiS is a simulation framework for WSNs which provides the functionality for simulating the nodes of network with their internal structure as well as the network between the nodes. One main feature of PAWiS is the contemporaneous simulation of the power consumption for each network node. The framework is based on OMNET++ and the user defined model that are written in C++ will be compiled to an executable simulator.

GloMoSim: GloMoSim is a project by UCLA to build a scalable network simulation environment for wireless and wired networks. Parsec's parallel discrete-event simulation capability is used in GloMoSim's design. Currently only protocols for purely wireless networks are supported and in the future, adding functionality to simulate wired and hybrid networks is in the future work. The simulator is available for both Windows and Linux platforms and is free for academic use.

OPNET: The OPNET Modeler is a commercial network simulator which offers a free academic licence. A GUI is available to configure the scenarios and develop network models. The topology of the network, behaviour of the nodes and the data flow inside the nodes and underlying protocols are determined under three hierarchical levels of network, node and process level respectively. The source code is based on C/C++. OPNET does not directly support the energy models of networks. OPNET is available on both Windows and Linux platforms but there is no support for Macintosh.

Ptolemy II: The Ptolemy project studies modelling, simulation and design of real-time, concurrent, embedded systems. The focus is on assembly of concurrent systems. The project is conducted in University of California at Berkeley. Sensor networks are one of the fields that Ptolemy can be exploited as modeller and simulator. There are Viptos is a tools that is specialized for sensor network design. This simulator is available in both Windows and Linux platforms.

Cell-DEVS: Cell-DEVS is an extension of DEVS formalism which is combined with Cellular Automata (CA). It is used for modelling the systems that are able to be represented as cell spaces. This simulator is available on UNIX based OSes, Windows platforms and Macintosh.

GTNetS: GTNetS is a network simulator environment that enables researchers in computer networks to study the behaviour of moderate to large scale networks. Various conditions are applicable using GTNetS. Trying to have a simulation structure much like the structure of the real networks, GTNetS has a clear and distinct separation of protocol stack layers. The versions of the software released after 2007 are supporting sensor models. Interested researchers may install the open source simulator on both Windows based and UNIX based platforms.

SystemC: SystemC is a language built in standard C++ by extending the language with the use of class libraries. Normally a combination of SystemC and other tools (i.e. OMNET++ or TLM) is used to simulate a wireless sensor network. The open-source environment is available both on Windows and UNIX platforms.

Prowler: Prowler is a probabilistic wireless network simulator which is capable of simulating wireless distributed systems. The simulation covers all the protocol stack from the physical communication layer to the application layer. The simulator runs under MATLAB and provides an easy way for application prototyping along with visualization capabilities. Although the simulator is designed to be a generic simulation environment, but it is currently targeting Berkeley MICA motes running TinyOS. While the simulator is using MATLAB environment it can be run on any platform that is supported by MATLAB including Windows and UNIX.

NCTUns: The NCTUns is an extensible network simulator and emulator. It can simulate different protocols used in wired and wireless IP networks. NCTUns is an open source simulator and is available for UNIX platform. EstiNet is the commercial version of NCTUns.

JiST/SWANS: JiST is a discrete event simulation engine which is able to run over a standard JVM. The simulation codes are written in Java, compiled using a regular Java compiler and run over a standard virtual machine embedded with simulation time semantics at the byte-code level. SWANS is a scalable wireless network simulator built atop JiST platform. SWANS is able to simulate much larger networks than NS-2 and GloMoSim. It employs the JiST design to achieve optimized memory usage and high simulation throughput. Benefiting from Java platform the simulator can run over any operating system that supports standard Java Virtual Machine. It is free for academic use and the source code is also available.

SSFNet: SSF is a public-domain standard for simulating discrete-events of large and complex systems in Java and C++. No source code for this engine is available. SSFNet is using the SSF engine combined with the code for simulation of networks, interface cards, hosts, routers and protocols that is available and can be adapted. The source code for the whole system is written in Java and for every operating system capable of running Java, the SSFNet is available to run on.

CONCLUSION

Developers of wireless sensor networks have serious challenges dealing with uncertainties of environment, density of development and limited energy, memory and communication resources. The issues related to node deployment, localization, energy management, clustering and data aggregation are of those which could be formulated as optimization objectives. The analytical methods suffer from slow or lack of convergence to final solution especially in case of having great number of nodes to be deployed. To solve such problems, fast optimization algorithms could be utilized to produce solutions both qualified and using less resources. GA and PSO are two overused techniques to solve the optimization problems in WSNs.

One of the disadvantages of using traditional methods to solve the problems in WSNs is the contradiction among different objectives of the application. For example reducing network cost will result in reducing network connectivity and coverage and providing network connectivity using high transmission power will lead to decrease in network lifetime. This property urges use of multiobjective optimization algorithms. The proposed approaches are both providing solution prior to deployment or after deployment. After deployment solutions are also divided into mobile node networks and active set management for dense deployments.

The research on multiobjective techniques in WSNs is still open and the future research could be on finding solutions that contain more parameters to have the results more close to real world, transferring the theoretical results into real-world applications, developing algorithms in hardware, making a parameterless black-box to provide solutions and extending the solutions to involve cross-layer approaches.

In this paper, an overview of multiobjective algorithms, issues related to WSNs, a review on multiobjective algorithms and the simulation environments are presented. Advantages and disadvantages of the solutions are presented. The high growth rate of multiobjective optimization algorithms is envisioning the use of these algorithms in various areas including WSNs.

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