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Multi-Objective Evolutionary Optimizations of a Space-Based Reconfigurable Sensor Network under Hard Constraints*

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Abstract

Wireless sensor networks have emerged as a promising way to develop high security systems. This paper presents the optimizations of a space-based reconfigurable sensor network under hard constraints by employing an efficient multi-objective evolutionary algorithm (MOEA). First, a system model is proposed for cluster-based space wireless sensor networks. Second, the statement of multi-objective optimization problems is mathematically formulated under multiple constraints. Third, the MOEA is used to find multi-criteria solutions in the sense of Pareto optimizations. Finally, simulation results are provided to illustrate the effectiveness of applying the MOEA to the multi-objective evolutionary optimizations of a space-based reconfigurable sensor network under hard constraints.

1 Introduction

Wireless sensor networks (WSNs) have received tremendous attention over past few years [1]. They can be widely applied to many applications, such as military, environmental, health, building, home automation, etc. Among these applications there is a particularly increasing need to develop low cost, highly sensitive, reconfigurable, and intelligent WSNs for space-based security applications. Space-based WSNs combined with geographical information systems will play an important role in developing future's global or local security systems. Technical advancements in Ad hoc networks, MEMS devices, low-power electronics, adaptive and reconfigurable hardware, micro-spacecraft, and micro-sensors have enabled the design and development of such highly integrated space wireless sensor networks for security applications [2–4].

However, there are many challenging issues which are specific to developing WSNs for space-based security applications. The limited power, reconfigurable topology, hardware adaptability, fault-tolerance requirements pertinent to the aerospace domain make the design and implementation of such a complex system even more challenging [4, 5].

Multi-objectives and constraints often arise from developing such a WSN for space-based security applications. These objectives are often competing or conflicting in essence, such as the coverage of sensor networks and the number of participating sensor nodes involved in the system which can be online reconfigured. Thus, to evolve the space-based reconfigurable sensor network under multi-objectives and constraints, efficient multi-objective optimization algorithms are necessary and crucial.

To efficiently solve the aforementioned multi-objective optimization issues, we have developed a specific MOEA (multi-objective evolutionary algorithm) framework which can span and evolve the whole sensor network from sensor nodes with reconfigurable hardware to cluster-based satellite network. Under this MOEA framework, the optimizers can concurrently drive both network and hardware resources to effectively and efficiently solve monitoring and diagnostic problems for space-based security applications.

2 System Modelling

The WSN considered in this paper has a cluster-based topology [6] in which there are a set of cluster heads. The cluster and whole network can be online reconfigured according to system requirements. Within each cluster there are a number of power-limited (only battery-powered) Pico-satellites (sensor nodes). Thus in this scenario, the networking lifetime of each sensing Pico-satellite is uniquely determined by its battery life assuming its orbital life is far longer than its battery life. However, the cluster head could be a Pico-satellite the same as the sensing satellite nodes or

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a bigger, more powerful mother satellite with rechargeable energy source from solar cells.

For each cluster, the sensing nodes directly send their collected data to the cluster head as in [6]. The cluster head will then transmit all the data it has received and generated to a remote base station such as ground station or another cluster head in a way of one or multi-hops. Let c and N denote the cluster head and the number of active sensing satellite nodes at any given time instant. It should be noted that the data from the N satellite nodes is simultaneously transmitted over a spread-spectrum bandwidth of W Hz.

In such a space-based WSN, like [6] the per-cycle transmission power and time (duration) also play important roles in determining the networking lifetime of each sensing satellite nodes within its orbital time. Let P_{ti} denote the transmission power for node i $(i = 1, \cdots, N)$ to transmit B_i bits during a transmission duration T_i. The different transmission rates are achieved by using variable spreading gains. Assume that the channel gain from the satellite node i to the cluster head c is h_i. Again, let γ_i denote the minimum bit-energy-to-interference-ratio threshold for the received signal from the satellite node i. T_i^{limit} and P_{max} represent the upper limit on the transmission delay and the maximum transmit power, respectively for the satellite node i. Thus, the quality-of-service (QoS) requirement for the satellite node i can be characterized by the triple $(\gamma_i, T_i^{limit}, P_{max})$ [6].

In the above system model, DS-CDMA can be found as its common application and BPSK is assumed as its modulation scheme. However, the analysis and results can be easily extended to accommodate more higher modulation schemes in such a cluster-based WSN [6]. As pointed out in [6], the system model can be employed to describe a wide range of WSNs, such as clock driven, event-driven, and inquiry-driven systems. If the cluster head c periodically broadcasts beacons to activate data transmissions from all the nodes in the same cluster, then the system model represents a clock-driven WSN. In an event-driven WSN, a subset of satellite nodes is simultaneously activated by the event to transmit their collected data to the cluster head.

To evolve this space-based WSN with a cluster topology under multiple objectives and constraints, we have developed a set of mathematical models for power consumption, pass loss, lifetime, and coverage, etc.

3 Statement of the Optimization Problems

3.1 Optimization of Energy Consumption

For the cluster-based satellite sensor network it is crucial to find the optimal transmission power P_{ti}^* and transmission duration T_{ti}^* of each satellite node i such that the total energy consumption of the whole cluster is minimized to transmit $\sum\limits_{i=1}^{N} B_i$ bits [6]. In the following let us denote $P_t = (P_{t1}, \cdots, P_{tN})^T$ and $T = (T_1, \cdots, T_N)^T$. The maximal number of the satellites available to form a cluster-based sensing network is $N_{\max}$. Thus, the optimization of energy consumption is expressed by:

$$\min f_1(P_t, T, N) = \frac{1}{\eta} \sum_{i=1}^{N} (P_{ti} + \alpha_{ci}) T_i \qquad (1)$$

Under the following hard constraints:

$$\begin{gathered} g_i(P_t, T, N) \geq \gamma_i, 0 < T_i \leq T_i^{\lim it}, 0 < P_{ti} \leq P_{\max} \\ 0 < N \leq N_{\max}, \;\; i = 1, \cdots, N \end{gathered}$$

where α_{ci} is the equivalent circuit power consumption, $g_i(P_t, T, N)$ is the received bit-energy-to-interference-density ratio at the cluster head c for the ith satellite, and given by [6]

$$\begin{aligned} g_i(P_t, T, N) = \left(\tfrac{E_b}{I_c}\right)_i &= \tfrac{W}{r_i} \tfrac{h_i P_{ti}}{\delta \sum_{j=1, j \neq i}^{N} h_j P_{tj} + N_c W} \\ &= \tfrac{W}{B_i} \tfrac{h_i P_{ti} T_i}{\delta \sum_{j=1, j \neq i}^{N} h_j P_{tj} + N_c W} \end{aligned} \qquad (2)$$

where $r_i = B_i / T_i$ represents the transmission rate and δ is the orthogonality factor denoting multiple access interference (MAI) from the imperfect orthogonal spreading codes and the asynchronous chips across simultaneous transmitting sensor nodes. N_c is the single-sided power spectrum density of AWGN, and W is the spread spectrum bandwidth. h_i is the channel gain of the ith satellite node.

It should be noted that the problem in question is not a convex optimization problem due to the presence of the product of P_t and T in the objective function $f_1(P_t, T, N)$ and the first constraint $g_i(P_t, T, N) \geq \gamma_i$ [6]. Hence, for this non-convex optimization problem one cannot say that a local optimization solution is the same as the global one. However, Shu *et al* in [6] has shown that such a non-convex optimization problem can be transformed into a more standard form which indeed has a special structure.

3.2 Optimization of System Lifetime

For WSNs, there are different definitions on lifetime. In the cluster-based satellite sensor network considered in this paper, we need to clarify three definitions of lifetime related to the cluster-based WSN system, i.e., orbital lifetime τ_{orb}, node lifetime τ_{nod}, and system (cluster) lifetime τ_{sys}. The node lifetime of the ith satellite is defined in this research as follows

$$\tau_{orb,i} = \frac{E_{b,i}}{P_i} = \frac{\eta E_{b,i}}{P_{ti} + \alpha_{ci}} \qquad (3)$$

where $E_{b,i}$ is the total energy of the ith satellite's battery. η is the efficiency of the power amplifier. Thus, the system lifetime of a cluster networked system with minimal number of requested satellite nodes can be formulated as

$$\tau_{sys} = \min\{\tau_{nod,1}, \cdots, \tau_{nod,N}\} \tag{4}$$

In this study it is assumed that $\tau_{orb} \geq \tau_{nod} \geq \tau_{sys}$. Suppose that the desired system lifetime is $\tau^* \geq \tau_{orb,i}, \forall i \in (1, N)$. The optimization of system lifetime can be stated as the following optimization problem:

$$\min f_2(P_t, T, N) = |\tau_{sys} - \tau^*| \tag{5}$$

Subject to:

$$0 < T_i \leq T_i^{\lim it},\ 0 < P_{ti} \leq P_{\max}, i = 1, \cdots, N$$
$$0 < N \leq N_{\max}$$

3.3 Optimization of Coverage

The space-based WSN in this paper is designed to monitor a critical area for security purposes. So the coverage is defined by

$$Coverage = Area\ covered/Total\ area\ of\ interests$$

Thus, the coverage optimization problem in this paper is given by

$$\min f_4(N) = 1 - Coverage \tag{6}$$

Subject to:

$$0 < N \leq N_{\max}$$

3.4 Optimization of the Participating Number of Satellites

The number of the participating satellites in a cluster needs to be minimized, i.e.:

$$\min f_3(N) = N \tag{7}$$

Subject to

$$0 < N \leq N_{\max}$$

4 Multi-Objective Optimization Algorithms

To solve the aforementioned optimization problems under multi-objectives and constraints, efficient multi-objective optimization (MOO) algorithm is needed. The essential requirement to a MOO is that it is capable to find Pareto-optimal solutions for the cluster-based satellite sensor network under multiple decision objectives and constraints. The aim is to provide the designer or end-user with a set of Pareto-optimal solutions from which to make a trade-off choice according to their own preferences and some practical limits. Among the existing MOO algorithms, MOEAs have been recognized as one of the possibly well-suited to multi-objective optimization problems [7].

The advantages of MOEAs include: (a) no need on derivatives or gradient information of objective functions in order to find the optima over the design variable space; (b) little knowledge about the problem being solved; (c) ability to tackle complex optimization problems which involve some intractable features such as discontinuities, multimodality, disjoint feasible spaces, etc; (d) robustness and inherently parallelity. Multiple individuals can search for multiple solutions simultaneously. They are more likely to find a global optima.

There are also many existing algorithms for MOEAs. Among these algorithms NSGA and its improved version NSGA-II [8, 9] have been applied to many applications so far. NSGA-II was developed by using a better sorting algorithm and incorporating elitism. Additionally there are no sharing parameter to be chosen as a priori. Therefore, in this study the NSGA-II [9] is adopted to develop a specific MOEA-based framework which can span and evolve the whole sensor network from sensor nodes with reconfigurable hardware to cluster-based satellite network.

5 Simulation Results

When N is fixed there are two objectives to be minimized. To investigate the effects of the distance between satellite sensor node and cluster head, the simulation was performed by varying the distance from 300m to 1500m for the case in which the number of participating satellites are fixed to be 3. Figs. 1-2 illustrate the Pareto front and optimal set under the different distance between satellite sensor node and cluster head. For the case in which N is variable and needs to be minimized, the simulation results are given in Figs. 3-4. It should be noted that in this simulation a simplified coverage model which describes the statistical relation between the coverage and the number of the evenly distributed satellite nodes was utilized to demonstrate the effectiveness of the MOEA. Since the number of the participating satellites also needs to be optimized in the second case, the length of chromosomes will be variable. This is another challenge in applying the MOEA to the multi-objective optimization problems considered in this study.

6 Conclusions

Wireless sensor network will play an important role in future's space-based adaptive systems for high security applications. There are often multiple objectives to be traded-off under multiple variable constraints. To investigate the

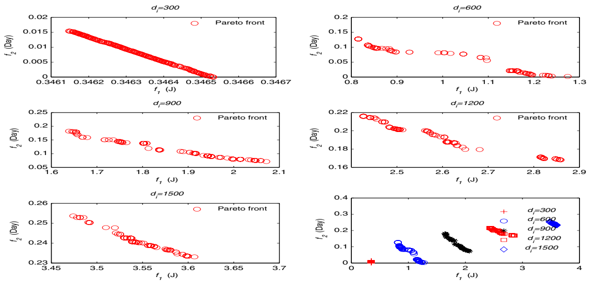

Fig. 1. Pareto Front under different distance ($N = 3$)

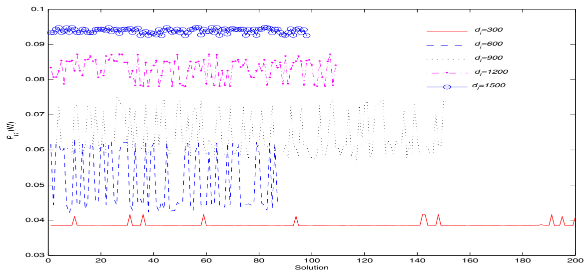

Fig. 2. Optimal transmission power for the 1st satellite node under different distance ($N = 3$)

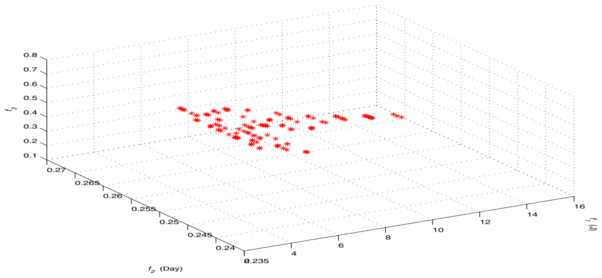

Fig. 3. Pareto front for the case in which N is variable

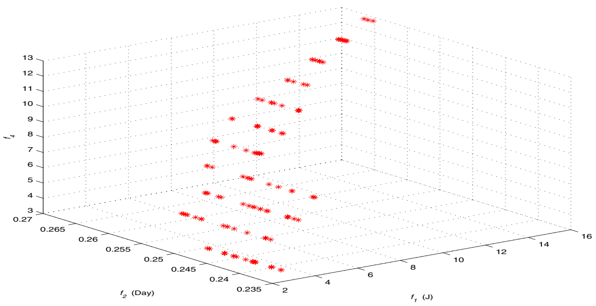

Fig. 4. Pareto front for the case in which N is variable (continued)

multi-objective optimization problems arising from such a space-based WSN system for security applications in future, this paper has proposed a system model for a space-based reconfigurable sensor network. The mathematical models for multi-objective optimizations under hard constraints have been developed. The statement of multi-objective optimization problems has also been formally formulated under multiple hard constraints. Thus, the MOEA can be applied to finding multi-criteria solutions in the sense of Pareto optimizations. As a result, the system designers or end-users will have more freedoms to make a reasonable trade-off choice from the set of Pareto-optimal solutions according to their own preferences and system requirements. The simulation results have been provided to demonstrate the effectiveness of applying the MOEA to the multi-objective evolutionary optimizations of a space-based reconfigurable sensor network under hard constraints.

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