

An adaptive approach to space-based picosatellite sensor networks

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ABSTRACT

The rapid advancements in ad hoc sensor networks, MEMS (micro-electro-mechanical systems) devices, low-power electronics, adaptive hardware and systems (AHS), reconfigurable architectures, high-performance computing platforms, distributed operating systems, micro-spacecrafts, and micro-sensors have enabled the design and development of a high-performance satellite sensor network (SSN). Due to the changing environment and the varying missions that a SSN may have, there is an increasing need to develop efficient strategies to design, operate, and manage the system at different levels from an individual satellite node to the whole network. Towards this end, this paper presents an adaptive approach to space-based picosatellite sensor network by exploiting efficient bio-inspired optimization algorithms, particularly for solving multi-objective optimization problems at both local (node) and global (network) system levels. The proposed approach can be hierarchically used for dealing with the challenging optimization problems arising from the energy-constrained satellite sensor networks. Simulation results are provided to demonstrate the effectiveness of the proposed approach through its application in solving both node-level and system-level optimization problems.

Keywords: Wireless sensor network, bio-inspired algorithm, multi-objective optimization, satellite, adaptive systems

1. INTRODUCTION

Technology advances have made it possible to deploy ad-hoc and flexible space sensor networks with hundreds of small, lightweight, low-cost satellites, usually known as picosatellites [1-4]. These picosatellites are associated with restricted constraints such as: be smaller than one cubic meter, weigh less than 1 kg, have ultra-low power consumption and low cost [3]. The space-based sensor network provides a novel way to distribute the functionalities of a large satellite into several smaller, less expensive satellites (such as picosatellites) to enhance the performance of future space missions through establishing an efficient ad hoc wireless sensor network in space[4,5]. The potential applications of space-based wireless sensor networks (WSNs) could include large-scale space observations, distributed imaging, remote monitoring for deep space exploration, cooperative sensing for high-resolution, synthetic-aperture radar, etc. Therefore, the space-based WSNs combined with geographical information systems (GISs) will play an important role in developing future global or local security systems [5]. Since satellites in a WSN work in a collaborative manner, the breakdown of some satellites in the network due to any reason would only partially affect the whole network. Therefore, satellite-based WSNs are more fault-tolerant and more reliable. It is very likely to recover the mission and functionality of malfunctioning small satellites by reconfiguring and distributing the satellites in the whole sensor network [5].

There is an ever increasing need to enhance intelligence and adaptive capability within picosatellites without sacrificing speed and power performance. This increases the importance of adaptation since these nodes are normally deployed in a wide range of space-based applications, and hence they need to adapt to the adverse space environment. For example, as the energy goes down, it may be preferable to have lower quality of data to make the picosatellites last longer. Since the satellites are often facing changing environments where different sensing missions may be required, they can be adopted to suit the needs of such changing environments by using adaptive and intelligent methods. On the other hand, as the number of nodes increases in a given satellite sensor network, there is also a need for efficient algorithms to be able to dynamically monitor these nodes and adaptively optimize the performance of each node and the overall network concurrently. In particular, this highlights the need for multi-objective optimization algorithms that are able to cope with conflicting objectives at the node and network (system) levels [6-7]. Furthermore, such algorithms are also desired to be

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amenable to hardware implementation with power and performance requirements for satellite sensor networks. For example, the optimization problems in a given satellite sensor network may range from dynamic optimization of smart antenna arrays to increase the efficiency to real-time optimization at system-level in order to effectively process and transmit distributed image and signal data to/from satellites in an ad hoc manner.

In this paper, we present an adaptive approach to space-based picosatellite sensor networks by exploiting efficient bio-inspired optimization algorithms, particularly for solving multi-objective optimization problems at both satellite and system levels. The rest of the paper is organized as follows. In Section 2, the related work is briefly reviewed. The proposed adaptive approach is described in Section 3. Section 4 validates the proposed approach by applying it to multi-objective optimizations of both satellite-level and system-level in a given satellite sensor network. Simulation results are also provided in detail in this section. The paper is concluded in Section 5 and the main contributions are also summarized there.

2. RELATED WORK

Although wireless sensor networks (WSNs) have received considerable research attention over the last decade [8-14], space-based sensor networks are only being focused on by some researchers in recent years [1-7, 15-18]. An “L2 mesh” protocol for space-based sensor networks was proposed in [4]. In this protocol directional antennas with a single transceiver per spacecraft to achieve low cost were used to deal with the large inter-spacecraft distances. They also presented a technique that derives the link activation schedule (transmit/receive mode and communications neighbor selection) and route paths used for multi-hop relay through the network. It was claimed that highly efficient communications were achieved, but neither the control policy nor energy optimization issue was mentioned.

Since the sensing and communication among the satellites in a satellite formation form the basis for the cooperative mission of the formation, the satellite formation is generally viewed as a mobile WSN in space. Therefore, the relative stability of communicating sensor topologies as a key characteristic of the formation of satellites and their behaviour as a wireless sensor network in space was studied in [16]. In this work, the topology of the sensing between the satellites and its influence over the stability of the formations were investigated. An interesting point was that the stability of the sensor network was mathematically analyzed. However, the optimization issues which are crucial in a satellite-based WSN were not addressed.

In [5], the real-time optimization of a cluster-based satellite WSN was investigated. The adaptive formation control and bio-inspired optimization were jointly dealt with for the cluster-based WSN in which multiple satellites fly in formation in the presence of unknown disturbances. Since there are always orbital disturbances such as gravity harmonics from a non-spherical Earth, atmospheric drag, and solar and lunar gravity, an adaptive formation controller is always needed. Otherwise, all these perturbations may tend to disturb the orbits from their ideal trajectories and cause the satellite-based WSN to disperse. Due to the purpose of adaptive formation control, real-time optimization is critical in this application to minimize the total energy consumption under the required quality of service by jointly optimizing the transmission power and rate for each satellite.

In recent years, there has been an increasing interest in applying efficient bio-inspired algorithms to space-based WSN for solving the emerging optimization problems in particular with multiple conflicting objectives [1,3,6-7,15]. The multi-objective optimal design of space-based reconfigurable sensor networks with novel adaptive MEMS antennas was investigated in [6] by using multi-objective evolutionary algorithms (MOEAs) [19]. The obtained multi-criteria Pareto-optimal solutions allowed system designers to easily make a reasonable trade-off choice from the set of non-dominated solutions according to their preferences and system requirements. The optimization of a space-based reconfigurable sensor network under hard constraints was presented in [7] by employing an efficient multi-objective evolutionary algorithm. For node-level optimization, a new approach for solving the multi-objective evolutionary optimization design of pipelined FFT processors for wireless OFDM receivers was proposed in [20].

3. AN ADAPTIVE APPROACH TO SPACE-BASED WIRELESS SENSOR NETWORKS

3.1 System Overview

In order to maximize the throughput and minimize the power consumption, the picosatellites in this research are composed of highly miniaturized System-on-Chip (SoC) devices tightly integrated with various sensing elements and communication units such as adaptive multi-band antennas. In this paper, the aim is to clearly present an adaptive approach to space-based picosatellite sensor network by exploiting efficient bio-inspired optimization algorithms,

particularly for solving multi-objective optimization problems in both node and system level. The proposed approach is developed to be hierarchically used for dealing with the challenging optimization problems arising from the energy-constrained satellite sensor networks.

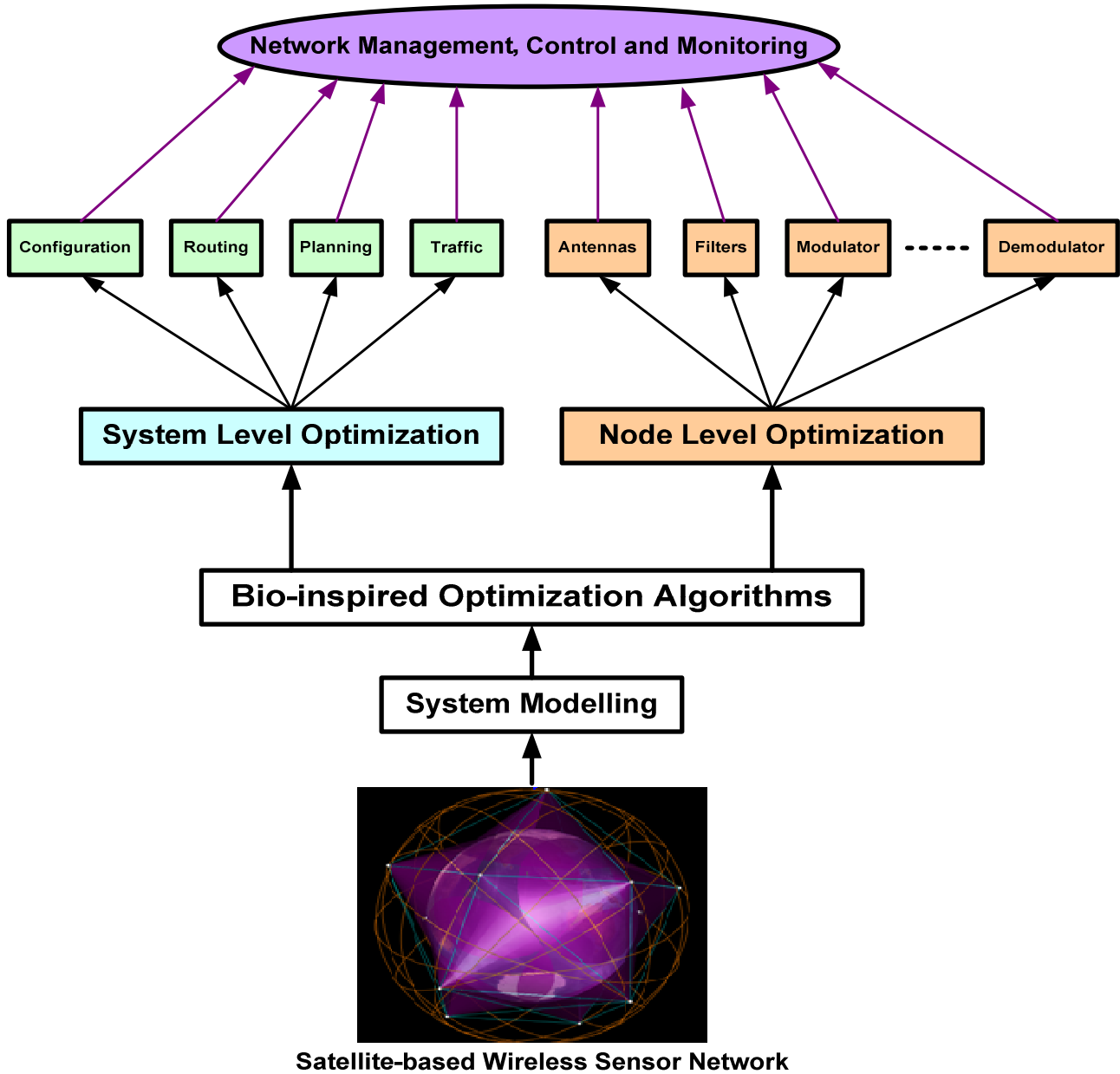


Fig. 1. An overview of the proposed adaptive approach to space-based wireless sensor network

A system overview of the proposed adaptive approach is shown in Fig. 1. From the figure, we can clearly see that the proposed approach can be used for the node-level and system-level optimizations. At the node-level optimization, a typical example is the adaptive antenna system which may consume up to 40% of the whole power consumption. Recently, studies have shown that reconfigurable MEMS antennas can reduce the antenna power by up to 50% through forming directed antenna beams instead of transmitting in all directions [21]. This is achieved by employing a micro antenna array and an optimization algorithm which dynamically optimizes and controls the array in real-time. As a result, the array antenna system is able to adapt its directional radiation pattern. However, this is an extremely time-critical application since the communications link can be lost and the adaptation goal cannot be achieved if the

optimization cannot be completed within the given time slot. Other example for node level optimization is the adaptation and configuration of the reconfigurable instruction cell based architecture implementing the communication baseband physical layer [25]. At system-level, optimization algorithms can also be used for routing the data through various satellite nodes in the most efficient way in order to save data transmission energy further and hence increasing the life time of the network as a whole.

3.2 Challenges

One of the key features in future integrated space-based sensor networks is the adaptation to internal or external changes in order to increase power efficiency and optimize the performance of the network as a whole. The task of replacing the energy system such as high-density battery array on up to thousands of picosatellites is impossible. Therefore, it is crucial to develop feasible methods for effectively managing power consumption at different levels of the network at both design and operation stage. This could range from network routing down to the architecture of individual picosatellites. However, it is a challenging problem to develop efficient methods for networking a large number of energy-constrained picosatellites. We are also facing the challenge of increased computational complexity when dealing with large scale, distributed, multi-modular, and non-convex problems arising from the energy-constrained satellite sensor networks.

3.3 Bio-inspired Optimization Algorithms

There is a need for new faster heuristics which can guarantee global optimality. In this research, we propose bio-inspired optimization algorithms to solve this problem as they offer many attractive advantages [1, 3, 15, 19]. First, they are non-gradient optimization methods and require little knowledge about the problem in hand. Second, bio-inspired algorithms normally have the ability to tackle complex optimization problems which involve some intractable features such as discontinuities, multi-modality, and disjoint feasible spaces. Third, population-based bio-inspired algorithms are robust and inherently parallel, which makes them attractive for parallel hardware implementations.

One particular challenge in solving optimization problems for applications in satellite-based space WSNs is that the solution space may have many local optima, which are substantially inferior to the global optimum, on which the traditional evolutionary algorithms [19] might get trapped. Moreover, most evolutionary algorithms proposed for general WSNs, e.g. genetic algorithms and particle swarm optimizations (PSO), can be easily trapped at local optima. To solve this problem, in the ESPACENET project [15], we have successfully developed two novel bio-inspired algorithms, namely an improved PSO algorithm (mPSO) [22] and a novel Shifting Balance Theory-based optimization algorithm (SBT) [23-24]. The improved PSO algorithm can keep all of the advantages of the standard PSO, such as implementation simplicity, low computational load, fast convergence, and few control parameters. Moreover, its convergence performance can be much better than the standard PSO algorithm [22]. In the SBT, for instance, a population is subdivided into many small demes, and connected by migration. In the simplest "island model", a fraction of individuals is replaced by migrants from the rest of the population. The convergence of the whole population towards the global optimum is separated into three phases: random drift that allows demes to explore the "adaptive landscape"; selection towards local optima; and spread of the fittest "adaptive peak" across all demes, aided by various kinds of between-deme selection [23-24]. In reality, the three phases would overlap, with random drift, and selection within and between demes occurring at the same time. The joint effects of random drift, selection between individuals within demes, and migration can be shown in Wright's island model.

Demes that are at superior peaks might be less likely to go extinct, or they might export a larger fraction of migrants [23-24]. For our new optimization approach, it is supposed that fitter demes have larger population sizes. More realistically, one could follow the joint stochastic process of population size together with allele frequencies or trait means. Our latest work has shown that the SBT-based approach is particularly efficient at finding the global optimum rather than being trapped at local optima [23-24]. Indeed, its capability of finding the global solution was found to be better than the currently popular PSO and Metropolis Algorithm (MA) [23-24].

4. SIMULATION RESULTS

Since energy is always limited or very expensive in most satellite-based sensor networks, energy-efficiency is of great importance for the design and operation of such an energy-constrained system, and has become one of the most important research challenges. Therefore, in this section we will demonstrate our proposed approach by applying it to

solving the optimization problems at both node and system level. Toward this end, an efficient multi-objective evolutionary algorithm tailored to suit the application in energy-constrained WSNs was used as follows [7].

4.1 Node-level modeling and optimization

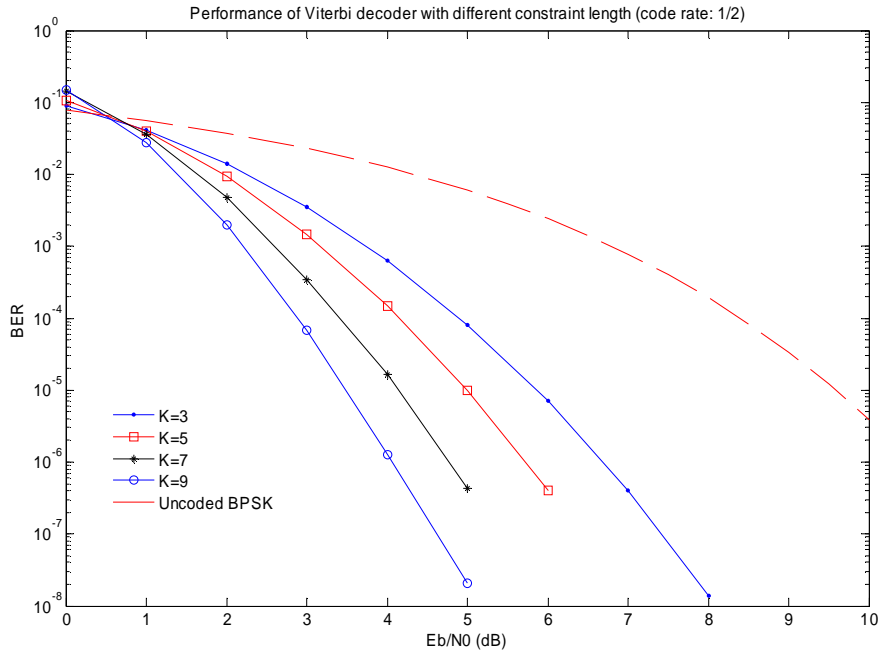
At the node level optimization, the proposed approach has been applied to solve the multi-objective evolutionary optimization design of pipelined FFT processors [20]. In this paper, we further demonstrate how the proposed approach can be used to solve other multi-objective optimization problems at the node level. Toward this end, a joint multi-objective optimization of a pipelined FFT processor and a Viterbi decoder is investigated. The design parameters are the wordlengths of each stage in the FFT processor since the precision and power consumption of pipelined FFT processors are highly affected by the wordlengths in fixed-point application systems. The details on the power consumption model and other design objectives for the FFT processors are seen in [20].

The corresponding parameters in the Viterbi decoder also need to be optimized simultaneously. For the optimizations in the Viterbi decoder, our research aims include:

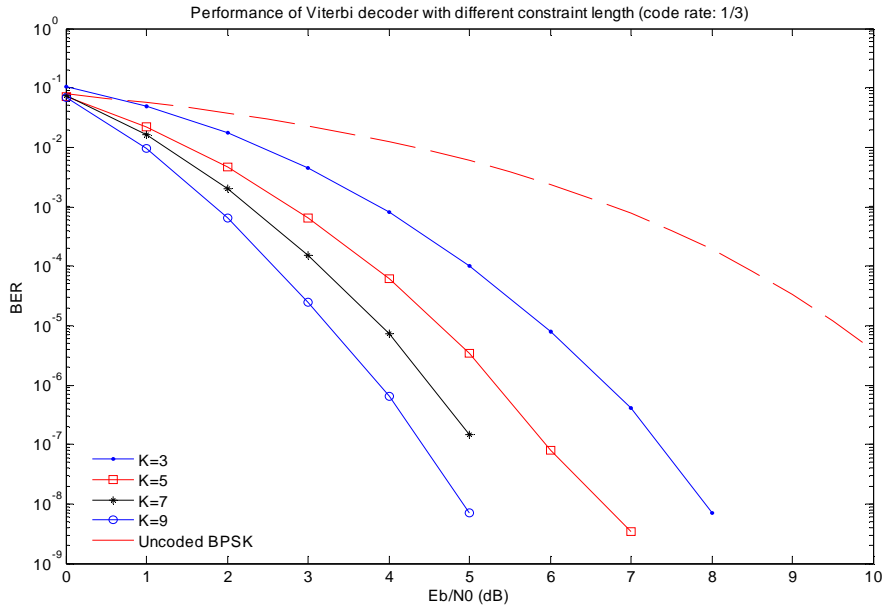
- a) to investigate how the constraint length K and code rate k/n affect the performance of a Viterbi decoder;
- b) to study the performance tradeoffs of the Viterbi decoder with the constraint length K and code rate k/n ;
- c) to know how much design space is available for optimizing a Viterbi decoder under multiple objectives.

Figure 1 shows how the performance BER (bit error rate) of the Viterbi decoder changes against the different parameters, i.e., code rate k/n , constraint length K , E_b/N_0 , etc. From this figure, we can clearly see that

- 1) Both constraint length and code rate have significant effects on the Viterbi decoder performance.
- 2) There is a need to make reasonable tradeoffs between BER and E_b/N_0 .
- 3) The relationship among BER, E_b/N_0 , constraint length, and code rate is complicated.
- 4) For a given E_b/N_0 , BER decreases while increasing constraint length K . However, E_b/N_0 can be reduced when the constraint length K increases, which means the transmission power can be decreased as a result of lower communication energy.
- 5) However, the computational complexity of the decoding algorithm grows exponentially with K , which will definitely result in an increasing power consumption of the Viterbi decoder.



(a) code rate: 1/2



(b) code rate: 1/3

Fig. 2. Viterbi decoder performance with different constraint lengths.

Thus control-action tables for BER and power consumption in the Viterbi decoder under consideration can be constructed, see Tables 1-2 and Figure 3, respectively.

Table 1. Control-action table for BER

Code Rate	K	Eb/No								
		0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
1/2	3	9.0793e-02	4.115e-02	1.4015e-02	3.4863e-03	6.3223e-04	8.1528e-05	7.0347e-06	4.0625e-07	1.3889e-08
	5	1.0768e-01	3.9706e-02	9.4194e-03	1.4643e-03	1.4909e-04	1.0069e-05	3.9931e-07	0	0
	7	1.4144e-01	3.6614e-02	4.7504e-03	3.4498e-04	1.6517e-05	4.2708e-07	0	0	0
	9	1.4969e-01	2.7890e-02	1.9756e-03	6.7399e-05	1.2778e-06	2.0833e-08	0	0	0
1/3	3	1.0565e-01	4.9743e-02	1.7509e-02	4.4587e-03	8.0626e-04	1.0123e-04	7.8056e-06	4.0972e-07	6.9444e-09
	5	7.2236e-02	2.2449e-02	4.6279e-03	6.4228e-04	6.0361e-05	3.3958e-06	7.9861e-08	3.4722e-09	0
	7	7.3423e-02	1.6049e-02	2.0174e-03	1.5541e-04	7.3125e-06	1.4583e-07	0	0	0
	9	6.8949e-02	9.6244e-03	6.5572e-04	2.4701e-05	6.3889e-07	6.9444e-09	0	0	0

Table 2. Control-action table for power consumption, mW

Code Rate	K=3	K=5	K=7	K=9
1/2	0.388	1.132	4.72	20.579
1/3	0.449	1.455	4.992	26.118

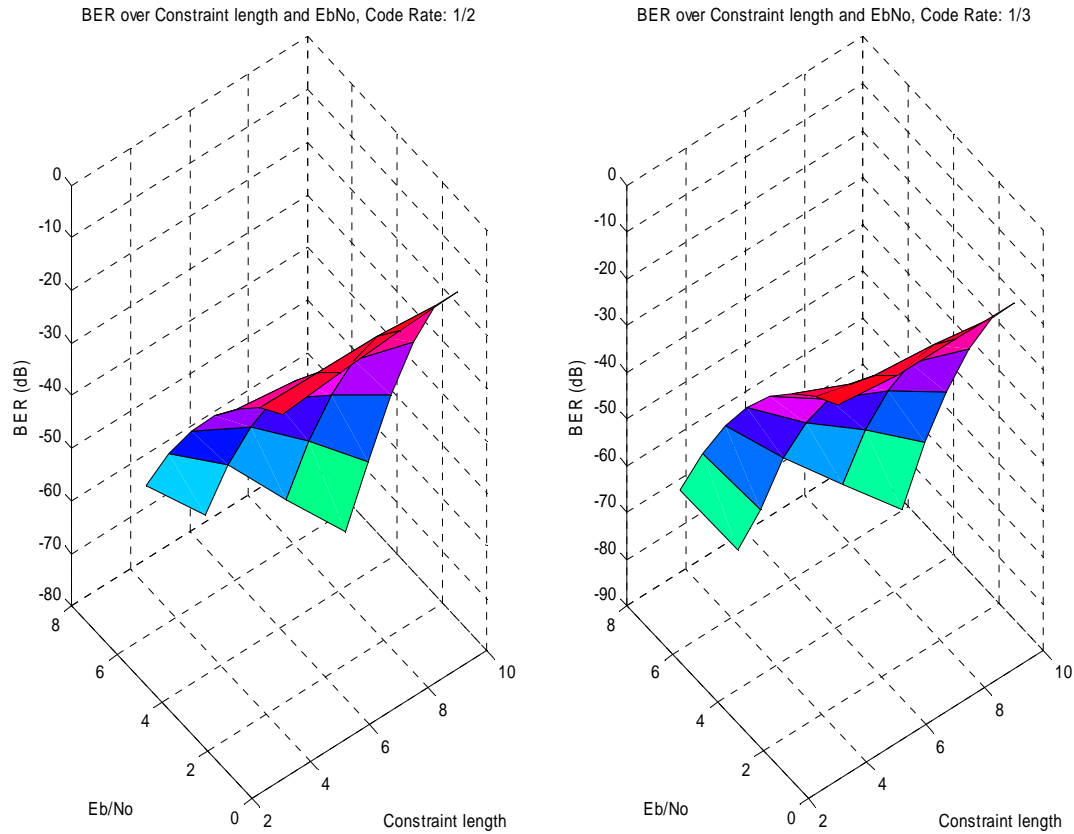


Fig. 3. Control-action surface for BER.

The parameters for the MOEA used in the simulation are given as follows:

- 1) Number of generation: 200;
- 2) Population size: 100;
- 3) Probability of crossover: 0.85;
- 4) Hybrid coding methods for chromosome, i.e. real-coded method is used for the FFT, while binary-coded is used for the Viterbi Decoder. The length of bits for each variable is 16;
- 5) Probability of mutation for real-coded: 0.15;
- 6) Probability of mutation for binary-coded: 0.01.
- 7) Number of objective functions: 4;
- 8) Number of variables: 12.

The FFT under consideration in this paper is set as follows:

- 1) 1K Pipelined fixed-point FFT.
- 2) The inputs and outputs of the FFT are set to 12 bits fixed-point numbers in the specification.
- 3) The desired SQNR (Signal-to-Quantization-Noise Ratio) is 35 dB.
- 4) The coefficients have a wordlength of 16 bits.
- 5) There is no scaling for all stages.
- 6) There are 2 objectives to be optimized, i.e., SQNR and power consumption.
- 7) The design variables are the wordlengths of each stage.
- 8) For 1K FFT, there are in total 10 variables ranging from 8 to 24.

The following is the setting for the Viterbi decoder:

- 1) Modulation scheme: BPSK (binary phase shift keying);
- 2) Convolutional encoding;
- 3) Channel model: AWGN (additive white Gaussian noise);
- 4) Optimization objectives: 2, i.e., BER and power consumption;
- 5) Decision variables: code rate k/n and constraint length K while E_b/N_0 is fixed at a specified level;
- 6) Full action tables are used.

The Pareto front obtained at node-level optimization is given in Fig.4. Figure 5 depicts the Pareto-optimal set. From Figs.4 and 5, the system designer or the network operator can dynamically make a trade-off among the four conflicting objectives in terms of the changing space environment and the varying space missions.

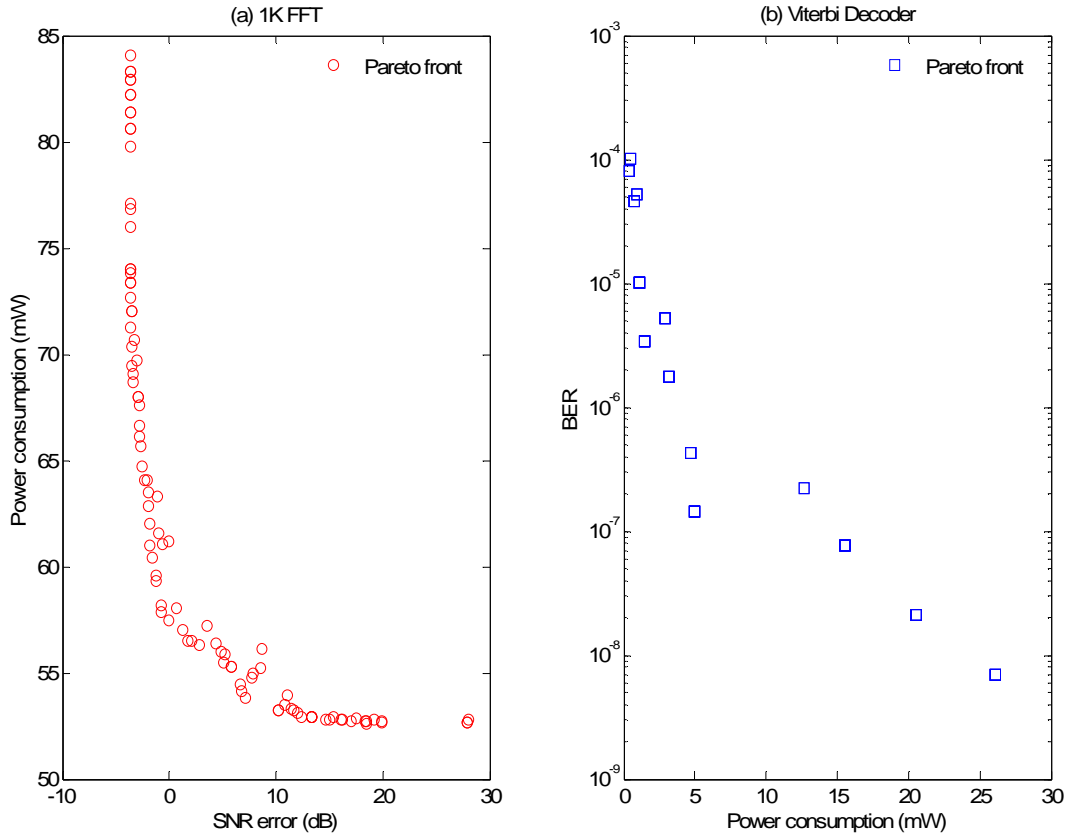


Fig. 4. Pareto front obtained in the node-level optimization. (a) 1K FFT processor. The x -axis represents the SQNR error defined by desired SQNR minus the actual SNR. The y -axis represents the power consumption (mW). (b) Viterbi decoder: The x -axis is the power consumption (mW). The y -axis is the BER.

4.2 Integrated system-level modeling and optimization

In this case study, we investigate how to effectively integrate the system-level and node-level multi-objective optimizations into a unified MOEA under the proposed adaptive approach. Since the whole system now includes a cluster-based satellite sensor network [6] and node-related components, such as the pipelined FFT processor and the Viterbi decoder, the complexity of the optimization problem with more objectives under hard constraints [7] is greatly increased. In the following simulation, the number of objective functions is 6 and the number of variables to be optimized is 18.

Figure 6 gives the Pareto-optimal set achieved in the system-level optimization. Now the complexity of making a trade-off decision has significantly increased since one has to take into account the 6 conflicting objectives from both node-level and system-level. The number of individuals on each ranked front over generations is shown in Fig.7. From this figure the performance of the MOEA can be visually evaluated through observing how the non-dominated front evolved at each generation.

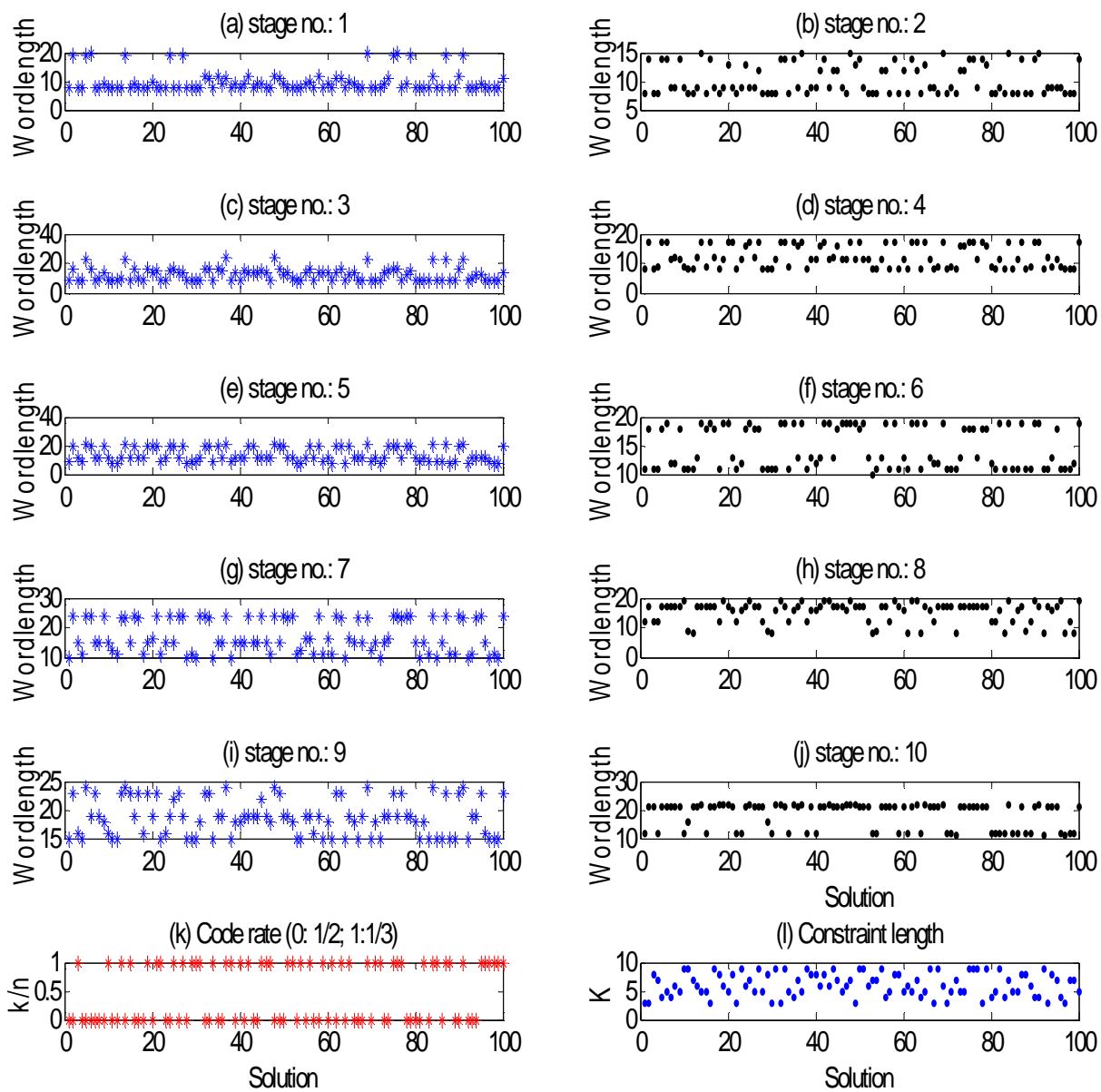


Fig. 5. Pareto-optimal set in the node-level optimization

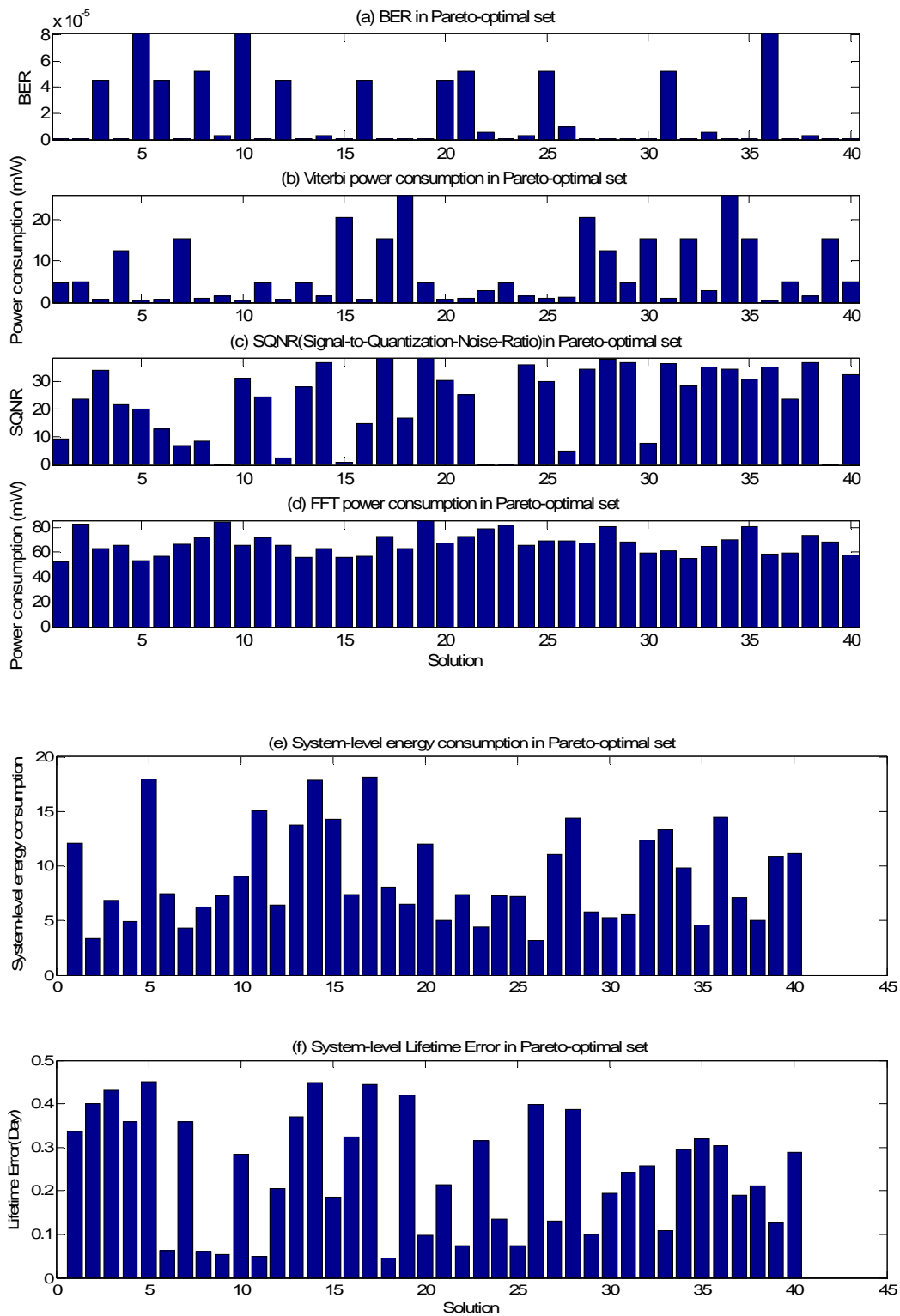


Fig. 6. Trade-offs of the conflicting Objectives in the system-level optimization.

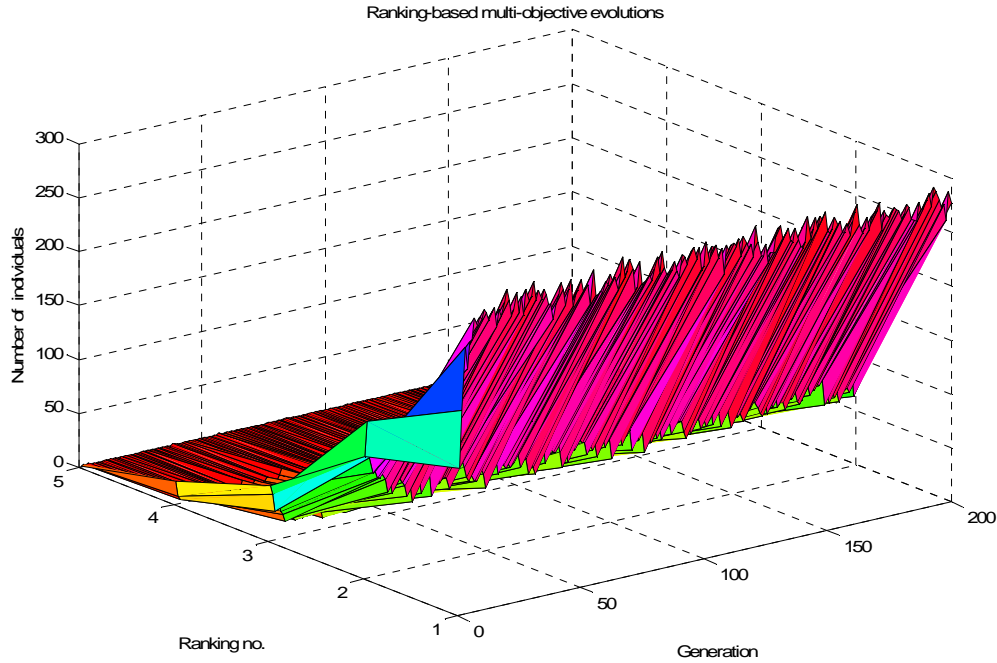


Fig. 7. Evolutions of the ranked fronts vs. generation.

5. CONCLUSIONS

Space-based WSNs have become an active area of research over the past few years. Massively distributed space-based sensor networks comprised of autonomous, miniaturized, intelligent, and very small satellites, in particular, have attracted a lot of interest in recent years for multipoint measurement applications in Low Earth Orbit (LEO). The space application domain presents unique challenges to sensor network design for balancing system performance and power consumption. Due to the extremely limited and expensive resources available onboard and the changing space environment as well as the varying space missions, fully adaptive approaches are particularly needed for both power savings and performance improvement in satellite-based WSNs.

In this paper, an adaptive approach to space-based picosatellite sensor networks has been presented by exploiting efficient bio-inspired optimization algorithms, particularly for solving multi-objective optimization problems in both node and system levels. In the proposed approach, the hierarchical utilization of efficient bio-inspired optimization algorithms at different levels with multiple objectives for dynamically optimizing the satellite-based WSN are essential. The simulation results obtained in this study have demonstrated the effectiveness of the proposed approach through its application to optimization problems at both node and system levels.

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