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Distributed Adaptability and Mobility in Space Based Wireless Pico-satellite Sensor Networks

Wei Li[1,2], Tughrul Arslan[2], Ahmed O. El-Rayis[2], Nakul Haridas[2], Ahmet T. Erdogan[2], E. Yang[2]
[1]*School of Electronic and Information Engineering, Xi'an Jiaotong University, China*
[2]*School of Engineering and Electronics, University of Edinburgh,*
Edinburgh EH9 3JL, United Kingdom
{W.Li, T.Arslan, A.El-Rayis, N.Haridas, A.Erdogan, E.Yang}@ed.ac.uk

Abstract

Collaborative networks of miniaturized satellite nodes demand new comprehensive and efficient distributed algorithms and protocols. The mobile nature of these nodes requires that these algorithms and protocols must be adaptive to ceaseless topology changes. This paper proposes an adaptive decision making function and weight factor targeting a highly efficient algorithm for distributed nodes. The new emerging algorithm aims to solve the above deployment problem. Other research work inspired by classical dynamics that study the movement of objects, called virtual force algorithm, is compared to the new algorithm in the paper. Our results demonstrate that the deployment algorithm using Decision Making function and distributed nodes' Weight Factor provide much more efficiency and savings in mobility energy than the existing algorithms.

1. Introduction

Space Based Wireless Satellite Sensor Networks (SBWSSN) is an emerging application based on traditional Wireless Sensor Networks (WSN) targeting compact, miniaturized, and multi-functional pico-satellites [15]. An SBWSSN retains the inherent features of WSN, at the same time presents further challenges such as limited energy supply to nodes, constrained communication distance, multi-hop information gathering and diffusion, all of which must be catered to, in the SBWSSN design. So far research has focused on high performance and low energy-consumption hardware design, long-range communication via adaptive beam-forming, and distributed adaptive algorithms for satellite mobility.

Satellites play a key role in modern human society. Some of these act as powerful remote sensors, which gather enormous information globally for both civil and military use; some act as communication infrastructure, which seamlessly connect the whole world coining the term global village. Satellites in space are one of the most expensive and sophisticated devices ever made by humans. They may become an important and easy target in future possible military conflicts between countries. Sophisticated pico-satellites must also be designed to withstand the harsh environment in space, and also survive the possible collision with tons of space junk that still orbit the earth. Replacing today's satellites with collaborative SBWSSN will greatly increase security, reliability and subsistence of satellite applications. Pico-satellites are more difficult to be targeted by weapons, even if some of the SBWSSN satellites are destroyed due to accidents or hostile intents, SBWSSN may still function fully by means of the remaining satellites. A SBWSSN approach is more agile when expected to self-organize the network to avoid any hostile attack, even a collision with debris or space junk.

One important feature of SBWSSN is that all the pico-satellites are dynamic in nature and can be considered as mobile-nodes in the network. The mobility of satellites in SBWSSN is essential to maintain or change their orbit and the formation in the network when collaboratively working with others depending on the application. Secondly, when considering the deployment problem of these pico-satellites in space, it would be impossible to manually place a large number of satellites in a specific manner to form the required network. The only way out is to have smart pico-satellites that adaptively deploy themselves to the target formation in an evolvable and self-organized manner. Thirdly, in some future applications, the SBWSSN can work as the guarding or monitoring system of larger space facilities such as space stations. In case of an emergency situation, the pico-satellites should be able to locate and track the threat or the problem. So the mobility of SBWSSN is an essential ability that each pico-satellite must have. This results in new challenges both in the design of satellite hardware and SBWSSN adaptive self-organizing software algorithms.

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The main research topics for mobile SBWSSN adaptive self-organizing software algorithms can be classified as follows:

- Adaptive distributed self-organised deployment
- Self-organized formation management
- Collaborative target tracking and space trash avoiding strategy
- Utilize mobility to increase communication ability and optimizing routing protocol behaviour

In this paper, we focus on the adaptive distributed self-organized deployment problem for SBWSSN. Our approach for solving this problem goes through the following steps. First, the goals of the deployment algorithm are analyzed. Second, by comparing the classical deployment algorithms utilizing mobility in normal WSNs, a special deployment algorithm for SBWSSN is developed. Third, this special deployment algorithm is implemented and its performance evaluated via simulations.

The rest of the paper is organized as follows. Background and related work on utilizing sensor mobility in Wireless Senor Networks and mobility handling issues are presented in section 2. Section 3 presents theoretical analyses on some factors relating to mobility in Space Based Wireless Satellite Sensor Network deployment and the design details of our algorithm in solving the deployment problem. Section 4 discusses simulation steps and results obtained. Finally, section 5 concludes the paper with its main contributions and future work.

2. Background and Related Works

Space Based Wireless Satellite Sensor Network is a special category of mobile sensor networks (MSN). Early research in MSN proved that even stochastic movement of the sensor nodes can improve the whole network throughput [1]. Sensor mobility and sink mobility have been discussed in [2, 3] and [4, 5], respectively. Mobile sensors can improve network coverage and target detection performance as studied in [3]. Also network lifetime can be maximized by changing the sink location and balancing the energy expenditure among the sensor nodes [4]. In addition, a more energy-efficient data dissemination protocol for WSN with multiple mobile sinks has been proposed in [5]. Security mechanisms that can tolerate compromised mobile sinks have been discussed in [6]. Furthermore, the authors of [7] discussed the problem of robots forming a geometric pattern as a potential military application in mobile wireless sensor networks. In [8], the author has proposed a new model to support mobile users in a wireless sensor network. In [9-12], the potential field approach was used to manage the mobility of an MSN to improve its sensing coverage.

3. Adaptive Distributed algorithm for self-organized SBWSSN deployment using satellite mobility

The SBWSSN in this paper is a general abstraction of possible future application of pico-satellites. Research on pico-satellites is gathering momentum with steadily emerging technologies [13] of integrated circuit design, system-on-chip design, micro-fabrication, micro-electro mechanical systems (MEMS), and micro-machining; making the SBWSSN almost reach the hardware requirement for real applications. On the other hand, lack of specialized protocols and algorithms dealing with the mobility of large self-organized network constrains the application potential. In this paper, we propose a distributed decision making method for satellite nodes to handle the mobility of SBWSSN deployment problem adaptively.

3.1 Assumption and deployment formation analyses

As there are a large number of nodes in the SBWSSN, we will consider the following assumptions for the algorithm. Each pico-satellite node needs to be working collaboratively with the others and sharing information with its own neighbors. All the nodes in the SBWSSN are uniform in functionality and ability. The neighboring nodes are those nodes located in one node's wireless communication range (Rc). Another range affecting the deployment formation is the sensing range Rs of the sensor applied on the satellite node. In some applications, the sensing range of the sensors on satellite is almost infinite. In such situations, we only consider Rc to affect the deployment formation as a special case. For a simple 2D representation both Rc and Rs are considered as ideal circles in this paper.

Another important assumption of SBWSSN is the measurement method and accuracy of the relative distance between any two nodes. Considering complexity and cost, satellite nodes are assumed to be able to measure the distance in-between each node using the wireless communication process. This ability is already a new function of IEEE 802.15.4 protocol; hence this assumption is quite reasonable. But this measurement method will definitely introduce some errors. In the simulation and results section, we will compare different approaches of the deployment algorithm with different degrees of measurement error.

Another assumption of satellite nodes is that each node can access information such as remaining energy level, total moving distance, and communication load of its real time neighbors. This serves the distributed nature of the algorithm.

3.2 Deployment formation

The purpose of utilizing mobility in deploying satellite nodes is to try and achieve the required coverage of the sensing field through a self-organized manner. At the same time, the nodes in SBWSSN are working collaboratively, which means each pico-satellite in the network must use its mobility to maintain its distance with other satellites within R_c.

Case 1: Full coverage

Assume that the sensor equipped on the pico-satellite has a limited sensing range, Rs. If a full coverage is required for the sensing field when Rc > Rs, the most efficient coverage is the hexagonal deployment with the distance between the nodes being Rs. If Rc < Rs, in order to maintain connectivity of the whole network, the nodes should be deployed with hexagonal formation with distance to others no more than Rc.

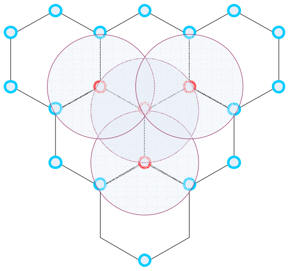


Figure 1. Full coverage of sensing field

Case 2: Partial coverage

For the case when it is not necessary to cover the entire sensing field, the goal of the deployment would be to try and cover the field with better efficiency. If Rc > 2Rs, there will be no overlap of sensing field of any two neighboring nodes. This will lead to a sensing gap within the network; this would be unacceptable if security is one of the main tasks of the SBWSSN. If the Rc/2 < Rs < Rc, there will be no sensing gap between the consecutive nodes, any interested targets passing through the field covered by SBWSSN will be sensed and reported. In this situation, deploying the nodes in hexagon formation and making Rs = Rc/2 will be the most efficient choice.

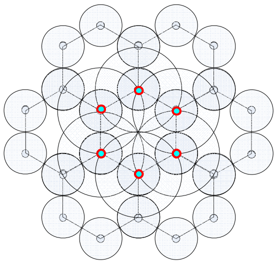


Figure 2. Partial coverage when $R_s = R_c/2$

3.3 Other deployment algorithms

One possible algorithm that can be used in solving the self-organized deployment problem is the Virtual Force (VF) algorithm [14], which was developed initially for mobile sensor networks. The algorithm deploys the nodes adaptively in a distributed manner; it only utilizes the position information of each node's neighbor. Fig 3 shows the final deployment formation reported in [14], where circles represent Rs. Both figures show that VF algorithm displays behaviors comprising with the full coverage case and partial coverage case discussed before. The essence of VF algorithm is keeping the nodes at distance equals to Rs and no more than Rc.

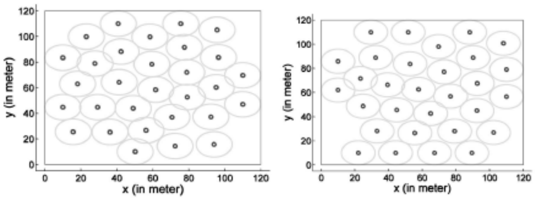


Figure 3. Final deployment formation of VF

There are some disadvantages of VF based algorithms.

- Vibration during converging to final deployment formation
- Costs more convergence time
- With out boundary or virtual boundary, the algorithm behaviours stochastic

The goal of our proposed deployment algorithm is to avoid the above disadvantages adaptively and in a distributed fashion.

3.4 Distributed deployment algorithm based on decision-making (DM) between nodes

To make up the final formation of Fig.1 and Fig.2 using the position information of the nodes and sensing field via a centralized method is quite an easy task. But making the whole process distributed and self-organized is quite complex.

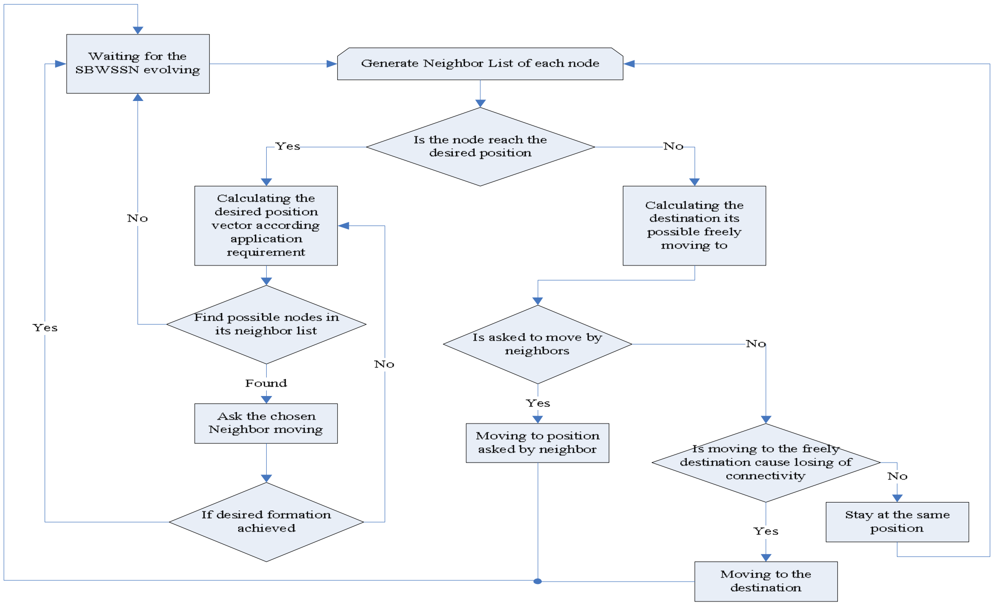


Figure 4. Flow chart of decision making of each node

The smart pico-satellite in SBWSSN is an intelligent device. Its computational ability makes the node capable of making decisions of its movement based on the information from its neighbors. When similar decisions are made by different nodes this may cause collisions. The nodes will be able to solve these collisions by means of negotiations through their wireless links. The VF algorithm does not use the nodes' intelligence, it just treats the different nodes as different parts of a physical mechanism system or as a molecule in Lennard-Jones potential from thermo-physics [12], [14]. That is the reason why VF algorithm has the disadvantages mentioned above and why it is less flexible than our algorithm which is based on decision-making between nodes. The decision making process of our algorithm running on each node can be illustrated by the flow chart in Figure 4.

Even after incorporating the DM algorithm within each node, there are still possibilities of a collision occurrence. This was observed when the algorithm has been simulated at the first stages of designing the DM algorithm. We then introduced a simple function on each node to decide which node gives out orders and which node follows orders during mobility. First, we normalize the energy levels of the N satellite nodes with a percentage of their initial energy, E_i. Then we use the present remaining average energy levels of the ith node's neighbors, E_i^{ave}. We also set a variable in the algorithm to represent the communication load of the node called L_i^c which should be integrated into the function. Since DM algorithm's main purpose is to deploy the SBWSSN, the communication load in this state is merely sharing position information, which is almost unique in the entire network. So we set this variable as a constant, which is needed after the deployment process. With all the above variables, we introduce the following Weight function:

$$W_i = \left\{ E_i \times \left(E_i - E_i^{ave} \right) + L_i^c \right\}$$

The larger the weight (W_i) of a node, the higher its possibility of giving out orders when a collision is expected. The value of $\left(E_i - E_i^{ave} \right)$ can be positive or negative. This shows whether a node is stronger or weaker among the neighbors, which is a key criterion used in the DM algorithm.

4. Simulations and results

We implement our DM algorithm for SBWSSN in C++, as well as the VF algorithm for comparison. As in [14], VF algorithm performs much better than other kind of algorithms and has proved its convergence on different shapes of the sensing field, and this is the reason why we did not implement any other algorithms for comparisons. The parameters used for VF algorithm are shown in table 1 which were set to be the same as in [14].

Table.1. Default VF settings

Parameters	Default values
Sensing distance Rs	10m
Communication distance Rc	30m
Maxima sensor speed	1m/s
Distance without Force	22m
Distance of Attraction	24m
Distance force vanish	26m
Time interval	1s
Stop criterion	0.1m

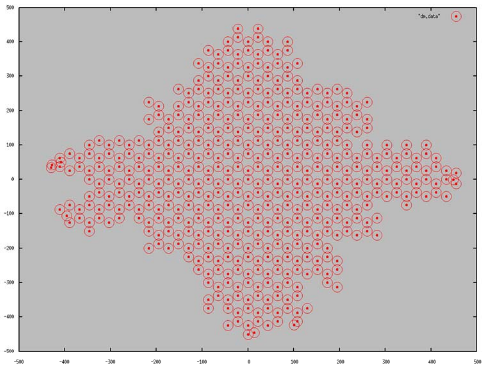
Table 2 shows the default values of parameters for our DM algorithm.

Table.2. Default DM settings

Parameters	Default values
Sensing distance Rs	15m
Communication distance Rc	30m
Maxima sensor speed	1m/s
Formation factor	Hexagon
Stop criterion	95% nodes

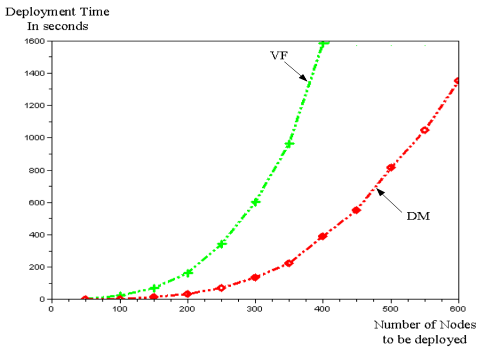
The stop criterion of our DM algorithm is when 95% of the nodes in the SBWSSN successfully find their position under the desired formation. Once this criterion is reached the deployment process is terminated.

The initial position of nodes before both deployment algorithms start is generated through the same stochastic function. But the initial boundary of the nodes is set to a very small value (20m by 20m). This is an assumption for the purpose of simulating the pico-satellites as being deployed in space from hatch on space station or space shuttle, or being launched by small rocket to carry them to a specific location.



Final Deployment Formation Using DM of 350 Nodes on Sensing Field

Figure 5. Final formation of DM



VF and DM deployment time

Figure 6. Deployment time of VF and DM algorithm

The final formation obtained by DM algorithm is shown in Figure 5. This figure shows that our DM algorithm can handle a very large number of nodes, and its final formation is almost similar to what we expected.

Satellites depend on their solar cells and battery for the purpose of wireless communications and operation of the electronic hardware. However the mobility of a pico-satellite comes at a price, due to the limited chemical propellants available to the satellite. So it is very important to conserve the mobility of pico-satellites. The longer the deployment process takes the more mobility energy will be consumed during this process. Therefore, in this work we have chosen the duration of deployment process as an important performance metric.

Distributed algorithms will take longer time as the number of single units in the system increases. But this kind of time increase has a nonlinear relationship with the number of nodes. We also run simulations with different numbers of nodes to evaluate the two algorithms' performance.

In figure.6 VF algorithm spent more time to implement the deployment with the same number of nodes as the DM algorithm. This is clearly proved by the simulations. The maxima number of nodes we simulated for VF is 400, because it will take too much time to deploy more nodes. Within the time that VF deploys 400 nodes, DM can deploy 600 nodes or more, which is a significant achievement.

As mentioned earlier, in real applications the measurement of distance may be inaccurate. This distance measure error will affect both deployment time and final formation in some degree. So we introduced position errors for each node artificially and repeated the simulations with different levels of errors. As shown in Figure 7, our DM algorithm still takes less deployment time than the VF algorithm.

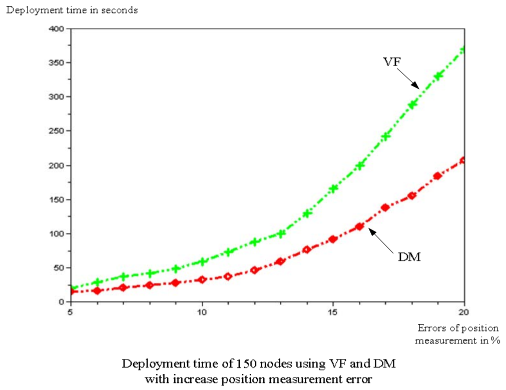


Figure 7. Deployment time of VF and DM algorithm

5. Conclusion and future work

In this paper a new adaptive deployment algorithm utilizing the mobility of pico-satellites in space based satellite wireless sensor network has been presented. The decision making algorithm is suitable for deploying satellite nodes in desired formations and orbits. The algorithm performs better than the Virtual Force algorithm mainly on deployment time, in other words, our algorithm uses less of the precious mobility energy of pico-satellites. Based on the presented results, we will be further investigating the mobility in SBWSSN, in order to improve communication bandwidth and the routing protocol. Efficiency and implementation in a 3D environment are other research issues which will be tackled in future study of mobility within the SBWSSN.

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