Ad Hoc Networks 25 (2015) 454–471

Contents lists available at ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

# Differential evolution-based autonomous and disruption tolerant vehicular self-organization in MANETs ☆

Stephen Gundry [a,*], Jianmin Zou [a], M. Umit Uyar [a], Cem Safak Sahin [b], Janusz Kusyk [c]

[a] Department of Electrical Engineering, The City College of New York, NY, USA
[b] BAE Systems – AIT, Burlington, MA, USA
[c] The United States Patent and Trademark Office, Alexandria, VA, USA

ARTICLE INFO

*Article history:*
Received 2 March 2014
Received in revised form 29 July 2014
Accepted 16 August 2014
Available online 28 August 2014

*Keywords:*
MANETS
Topology control
Differential evolution
Bio-inspired algorithms
Autonomous mobile nodes
Fault tolerant networks

ABSTRACT

Mobile ad hoc networks (MANETS) can be useful for providing network coverage in harsh and adversarial environments in many commercial and military applications where nodes may become randomly or systematically disabled. For these networks to be reliable and scalable, robust topology control algorithms must be developed to guide the deployment and geometric configuration of mobile nodes without a priori knowledge of the terrain. This article studies a disruption tolerant topology control mechanism based on differential evolution, called TCM-Y, that directs the movements of autonomous vehicles to efficiently and dynamically deploy themselves into a uniformly dispersed configuration. TCM-Y uses a Yao graph inspired fitness function to maintain a minimum desired number of connections for a node with its neighbors while uniformly dispersing autonomous vehicles over an unknown terrain.

We present a formal analysis of TCM-Y to show that it provides a disruption tolerant node spreading mechanism since any node will have at least $k$ neighbors at all times. The performance of our TCM-Y was tested in hostile environments where nodes systematically or randomly experience hostility and become disabled. The results from simulation experiments show that mobile nodes running TCM-Y perform well in the face of neighbor losses with respect to NAC, ADT, and average connectivity, while limiting the number of network partitions that may occur as a result of node failures. The effectiveness of TCM-Y was evaluated by comparing it with a popular non-deterministic node spreading mechanism that has similar objectives as TCM-Y. The assessment shows that TCM-Y performs significantly better with respect to average connectivity, pre-defined minimum number of neighbor connections, and average distance traveled at the expense of lower normalized area coverage. We also developed a testbed to perform real-time experiments with our TCM-Y implemented in laptops to guide the movements of human operators towards a uniform distribution of mobile nodes. Real-time experiments performed on the testbed verified the results from our simulation experiments.



## 1. Introduction

In many military and commercial applications autonomous vehicles may experience systematic or random disruptions due to natural disasters, hostile activities, or other events that incapacitate network infrastructure. Mobile ad hoc networks (MANETS) can be deployed for these types of mission critical and time sensitive activities such that mobile nodes can deploy themselves in unknown

☆ Earlier versions of this work was supported by U.S. Army Communications-Electronics RD&E Center Contracts W15P7T-09-CS021 and W15P7T-06-C-P217, and by the National Science Foundation Grants ECS-0421159 and CNS-0619577. The contents of this document represent the views of the authors and are not necessarily the official views of, or are endorsed by, the U.S. Government, Department of Defense, Department of the Army or the U.S. Army Communications-Electronics RD&E Center.

* Corresponding author. Tel.: +1 718 982 3021.
*E-mail address:* sgundry00@citymail.cuny.edu (S. Gundry).

http://dx.doi.org/10.1016/j.adhoc.2014.08.006
1570-8705/

territories, adjust their locations when the terrain changes, and provide disruption tolerant connectivity. Autonomous topology control algorithms give unmanned vehicles the ability to decide their own movements and perform network tasks without a centralized controller. In addition, these dynamic and decentralized methods for topology control must be highly scalable and tolerant to autonomous vehicle failures (see Table 1).

In this article, we provide a differential evolution (DE) based disruption tolerant vehicular self-organization for MANETS, where each autonomous vehicle determines its movements based on the information within its local sensing area to create a MANET that is scalable and tolerant to node failures. With this vehicular self-organization mechanism, called TCM-Y, each autonomous vehicle uses DE [1] with a Yao graph [2] inspired fitness function to adjust its position while maintaining connectivity with a pre-defined number of neighbors at all times.

### 1.1. Our existing research

In our earlier work, we presented preliminary results for our DE-based topology control mechanism (called TCM-DE) to uniformly disperse autonomous mobile nodes over an unknown deployment area [3]. Uniformity metrics for the performance evaluation of TCM-DE are presented in [4]. We introduced TCM-Y in [5] and experimentally demonstrated that, for the disruption-free case, it maintains connectivity with a pre-defined number of neighbors while spreading autonomous vehicles. In [6], we present an initial sketch of formal analysis for TCM-Y to show that it will maintain a pre-defined minimum number of neighbor connections while dispersing mobile nodes to a targeted network topology. To demonstrate the efficiency of TCM-Y, we implemented simulation software using MASON [7] libraries. The preliminary results for TCM-Y performance was compared to a popular mobile node dispersion mechanism [8]. In [9] we report the initial results for performance evaluation of our TCM-Y to uniformly spread autonomous vehicles and maintain connectivity with a pre-defined number of neighbors in harsh environments where nodes become incapacitated due to random node failure or destruction.

**Table 1**
Definitions of variables.

| Variable | Definition |
|---|---|
| $R_{com}$ | Communication radius |
| $R_{mov}$ | Longest distance in a single step within $R_{com}$ |
| $N_i$ | Autonomous vehicle |
| $\mathcal{N}_i^t$ | Chromosome for node $N_i$'s current location |
| $\overline{X}_{i,0}^{t+1}$ | Set of randomly selected speeds and directions |
| $\tau$ | Number of generations |
| $X_{i,\tau}$ | $i$th Generation at population $\tau$ |
| $x_{a,\tau}$ | A potential solution |
| $v_{a,\tau}$ | A mutant solution |
| $F$ | Scale factor in the range of $[0, 2]$ |
| $u_{a,\tau+1}$ | A trial solution |
| $b$ | Each of $D$ dimensions contained in the chromosome |
| $\psi(b)$ | Uniformly distributed random number in the range of $[0, 1]$ |
| $CR$ | Crossover threshold in the range of $[0, 1]$ |
| $\phi$ | Randomly chosen index of the mutant solution |
| $\tau_{max}$ | Final generation |
| $x_{best}$ | Fittest movement decision found after $\tau_{max}$ generations |
| $\rho$ | Number of Yao partitions within communication radius |
| $Y_f$ | Number of Yao partitions occupied by autonomous vehicles |
| $d_{min,p}$ | Distance to the closest autonomous vehicle within partition $p$ |
| $Y_\delta$ | Set of mobile nodes that are closest in each Yao partition |
| $k$ | Amount of fault tolerance for vehicles running TCM-Y |
| $F_{max}$ | Penalty fitness |
| $d_{crit}$ | Distance between a candidate location and the critical neighbor(s) |
| $\varphi_{j,j+1}$ | Angle of separation between two adjacent neighbors $j, j+1$ |
| NAC | Normalized area coverage |
| ADT | Average distance traveled |
| $f_{Y_{\delta,k}}$ | Fitness for node $Y_{\delta,k}$ |
| $d(N_i^0, N_i^t)$ | Total distance traveled by node $N_i$ up to time $t$ |
| $\|I\|$ | Set of all nodes in the deployment space |
| $\delta_{avg}$ | Average connectivity |
| $\Phi$ | Number of network partitions |
| LR | Loss rate |

### 1.2. Contribution of this article

This paper builds on the results from our previous work where TCM-Y and the performance metrics were introduced. In this paper, we expand the existing research with the following contributions. The formal analysis of TCM-Y is extended such that there are new theorems and a lemma proving uniform coverage with different geometric configurations of autonomous mobile nodes. We present the results of over 1000 simulation runs to evaluate the performance of TCM-Y for various parameters including the minimum number of neighbors and node loss rates for harsh environments. This analysis shows that, as the pre-defined minimum number of neighbor connections $k$ is increased, TCM-Y improves the average distance traveled (ADT), average connectivity and avoids network partitioning; however, these performance gains are achieved at the expense of the normalized area coverage (NAC) since the mobile nodes remain tightly bound together for larger $k$, and hence, spread themselves less far apart. We performed simulation runs to compare TCM-Y with a popular non-deterministic algorithm, called the Artificial Bee Colony (ABC) algorithm [10] and show that TCM-Y outperforms ABC. We demonstrate that TCM-Y is disruption tolerant in harsh environments where nodes systematically or randomly experience hostility and become disabled. TCM-Y exhibits these capabilities without requiring global information nor synchronization between autonomous vehicles. We also developed a testbed implementation of our TCM-Y to verify the performance observed in simulation experiments. In this testbed human operators carry laptops, each of which autonomously runs TCM-Y to direct operator movements by voice commands. The results of the real-time experiments show that TCM-Y is an effective tool to uniformly spread autonomous mobile nodes and preserve network connectivity.

### 1.3. Article organization

Section 2 of this article reviews prior research on topology control in MANETS and the use of DE for the deployment of autonomous vehicles. In Section 3, we present our TCM-Y.