Optimizing Tactical Military MANETs With a Specialized PSO

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***Abstract*—An agent location optimization model for military mobile ad-hoc networks is described. A mobile ad-hoc network (MANET) is a self-configuring network of autonomous agents designed to continuously support users who change the topology of the network dynamically and independently. The autonomous agents are controlled to maximize the connectivity of user nodes that move within the target region considering tactical military aspects. The primary objective of the agent location model is to maximize the connectivity and quality of communication between user nodes and a control node. To support military applications, a new approach, the Pre-deployed Agent Level (PAL) is introduced and a particle Swarm Optimization (PSO)-based heuristic with PAL is developed to solve the problem under three user mobility models. The focus of the paper is to determine the effect of PAL on the communication quality in the network.**

I. Introduction

A mobile ad-hoc network (MANET) is a self-configuring network of autonomous agents designed to continuously support users who change the topology of the network dynamically and independently. The dynamic mobility of user nodes can cause communication links to disconnect if the network is not managed correctly. The autonomous agents' movements are controlled to maximize the connectivity of user nodes considering military aspects. Under these requirements and circumstances, the primary objective of the agents is to maximize the connection and quality of communication between user nodes and a control node. Because of the need for quick and effective optimization, a population based heuristic algorithm, Particle Swarm Optimization (PSO), is developed to solve the military MANET problem. To best accommodate the aspects of military MANETs a Pre-deployed Agent Level (PAL) construct is developed and examined [4]. Testing involves the common random waypoint user mobility model and two specific military user movement models - search and rescue and convoy to destination.

Mobile Ad-hoc Networks (MANET) are based on wireless cellular technology to overcome the limitations in an environment that does not have readily available infrastructure [3]. Nodes in a mobile ad-hoc network are free to move and organize themselves in an arbitrary fashion. The path between each pair of users may have multiple links and the communications used can be heterogeneous if the network devices have different configurations. This allows an association of various links to be a part of the same network.

The developed PSO deploys the autonomous agents to the best locations at each time step based on user and obstacle node locations and transmission requirements. All nodes have predefined velocity and transmission ranges and user nodes move freely around the tactical operation area. The decision variables that define the optimal solution are the agents' directions and magnitudes of motion at each time step.

In order to make the model more realistic in a military environment, we have incorporated three military-related aspects that are not common in the MANET literature. First, we define four node types, including user nodes (which are responsible for carrying-out military missions), agent nodes (which are responsible for maintaining communications), priority nodes (which are user nodes that have a higher connection priority that normal user nods), and control nodes (which are responsible for controlling the movement of the agent nodes).

Second, enemy obstacles that limit communications are incorporated in the model. An enemy obstacle can impair communications when a node enters a given region around the obstacle. Finally, a messenger option is implemented. The messenger is not a new resource, but an agent that has a temporary mission to search a limited area for recently disconnected users.

A heuristic algorithm is developed to find the efficient network paths for the military scenarios by using the hop-count and bandwidth network performance metrics along with the newly defined construct, Pre-deployed Agent Level (PAL). Minimum hop based routing is a popular method in mobile ad-hoc networks and is suitable for military MANETs. The hop-count is the number of hops separating a source node from its destination along the minimum path [7]. That is to say, it is the number of links passed by a packet between a source and a destination node. The strong points of this method are simplicity and lower consumption of network resources than the shortest-distance path [6]. However, minimum hop routing does not take into account the link quality and stability [5]. In particular, it does not consider the potential pre-deployment of agent nodes to support user movement. Consequently, hop-count alone will generally not provide the optimal network performance in our target environment. In response, PAL was developed and used in this study to deal with this problem. The work described herein is aimed at analyzing the effect of PAL on the communication metrics of optimally designed networks, that is, networks with agents' movements selected by the PSO to maximize communication.

II. BACKGROUND

Wireless multi-hop networks are generally modeled as communication graphs. In a wireless multi-hop network, each node has a certain transmission range, and is able to send messages to other nodes within its own transmission range. The existence of each edge in the network is determined by the transmission ranges of potential end nodes. Therefore, the connectivity of a network depends on the transmission ranges and locations of all nodes. In terms of communication networks, all nodes of a connected network can communicate with all other nodes over one hop or multiple hops, whereas in a disconnected network we may have several isolated sub networks that cannot communicate with one another. Connectivity is a function of the number and locations of the nodes and the wireless transmission ranges [1].

Mobile nodes in a wireless network operate on a battery supply, so mobile nodes naturally have critical power constraints and network life depends on the efficient use of this resource. In military applications, the number of relay nodes tends to be small and all wireless communications share this limited number of relay nodes. Therefore, unnecessary transmission should be minimized, that is, hops should be minimized. Moreover, additional hops increase the delay of transporting data packets due to the additional buffering, contention for resources, and transmission time required.

For military MANETs, we functionally divide military operation units into three groups: command/control, execution, and support. The command/control unit, which is represented by a control node, manages all of its assigned subordinate units.

Execution units, which are represented by user nodes, perform the commands received from the control center or the higher unit in the command/control hierarchy. Of course, the execution units could exchange valuable information with each other over the network, but the decision making of important actions directly related to a given mission is performed through communication with the control center. Finally, support or service units, which are represented by agent nodes, seek to provide all units in an operation network with a tight communication relay service for enabling military operation functions such as command/control, information acquisition and exchange, and execution required for mission accomplishment.

The nodes representing network devices in the mobile ad-hoc network are generally divided into user (client) and agent (server) nodes in the literature reference. But considering the nature of military operation discussed above, those nodes need to be further specified to represent realistic scenarios. So, we have extended the general classification with four different types of nodes: control, agent, user and priority nodes. The classification and brief descriptions of each category are given as follows:

Agent node - The support unit described above is represented by an agent node. The agent node is responsible for connecting network nodes positioned beyond their communication ranges in a network to maintain the network at the best condition possible. For this purpose, agent nodes are repositioned based on the information about the location of the network nodes and the communication capabilities using the distances between nodes.

Control node – The command/control center is represented by the control node. The command/control center in military operations plays a key role of controlling agents in the network to perform a given mission. Particularly, the control node in this research performs two additional tasks. It is responsible for supporting user nodes like other agent nodes and it designates any user node required for a tighter connection with the control node as a priority node, which has priority for network service.

Unlike traditional MANET models, user nodes are divided into two types, user and priority in this military MANET. The user and priority nodes represent a variety of combat or forward military units from individual soldier to battalion military unit level or greater. These user nodes are free to move according to their mobility characteristics within a tactical theater.

User node – User nodes represent an individual soldier or a military combat unit at a variety of organizational levels. The user nodes require network service while moving around the tactical space.

Priority node –Any user node which is considered as an *important* node related to the tactical situation can be designated as a priority node by the control center. Priority nodes have preference over user nodes to be connected to the control node since MANET has a limited number of agent nodes.

The connections between network nodes are defined by their signal strengths and the network connection for a network node in this research means that the network node is able to communicate with the control node. Therefore, any network node that is disconnected from the control node is referred to as an isolated node. However, in order to accurately represent the network states corresponding to an environment change, more distinctive definitions for possible cases are required. First, the exact definitions regarding isolation are as follows:

- *Isolated user* – Disconnected with the control and all agents
- *Isolated agent* – Disconnected with the control and all users
- *Isolated user-agent cluster* – One or more agents and/or one or more users connected together, but disconnected from the control node

Based on these definitions of isolated nodes, two network states (States 1 and 2) are defined in this research. If there is no isolated user in the network, the network is State 1. Otherwise, it is in State 2. The network state is used to determine the precise network evaluation method to be used in the optimization. The complete problem formulation is given in [4]. For the purposes of this paper, we describe the primary and secondary objectives only.

Primary objective

$$\max\{\lambda_1 N_U + \lambda_2 N_A + \lambda_3 P + \lambda_4 L\} \qquad \text{Eq. 1}$$

Where:

λ_1, λ_2, λ_3, and λ_4 are weight parameters,
N_U is the number of connected user nodes,
N_A is the number of connected agent nodes,
P is the PAL metric, and
L is the number of agent-user links

Secondary objectives

$$\max\{BW/CC\} \qquad \text{Eq. 2}$$

Where:

BW is the total bandwidth for the network, and
CC is the sum of the distances from the agent nodes to the control node.

$$\min\{SR\} \qquad \text{Eq. 3}$$

Where:

SR is the distance between the messenger agent and the expected position of the corresponding isolate node.

Regardless of the network state, the primary optimization objective function is given in Eq. 1. The objective combines the number of connected users, the number of connected agents, PAL (described below), and the number of user-agent links (all evaluated at each time step). The secondary objective is used only to select from among alternative optimal solutions with respect to the primary objective. If the network is in State 1, Eq. 2 is used as the secondary objective, and if the network is in State 2, Eq. 3 is used as the secondary objective. The basic idea here is that, if the network is completely connected, the secondary objective is to maximize the bandwidth-to-*CC* ratio; otherwise (the network is in State 2), the secondary objective is to minimize the *SR* -- the distance between the messenger agent and the expected location of the disconnected user.

The PAL construct is designed to distribute the agent nodes as widely as possible in an effort to support future user node movement. This avoids near term duplication and inactivity of agents, and future term disconnectedness. PAL simultaneously requires each agent node to support at least two user nodes and penalizes instances where multiple agents support the *exact* same sets of user nodes -- the basic idea being that multiple agents supporting the same set of users is redundant. As such, PAL involves explicitly considering the sets of user nodes supported by the individual agent nodes at each time step. The mathematical formulation of PAL is given in below:

$$PAL = \left(\sum_{i=1}^{TU_t} uPAL_i + \sum_{i=1}^{TA_t} aPAL_i \right) \qquad \text{Eq. 4}$$

$$aPAL_i = \begin{cases} 0 & \text{if } SU_{it} \text{ is identical to } SU_{jt} \text{ for any agent node, } i \neq j \\ 1 & \text{otherwise} \end{cases}$$

$$uPAL_i = \begin{cases} 0 & \text{if } SA_{it} \text{ is identical to } SA_{jt} \text{ for any user node,} i \neq j \\ 1 & \text{otherwise} \end{cases}$$

Where *u* denotes user nodes, *a* denotes agent nodes, *SU* denotes supported users and *SA* denotes supported agents.

The experiment is conducted based on three different user mobility models in order to compare network performance under different military-related operational environments. The random waypoint is very common in MANET research as a default mobility model [2]. User nodes under this mobility model move randomly around the operation area without being directed by a control unit or an operational plan.

The CD (convoy to destination) movement pattern represents a military operation convoying a core body to a destination. A core body, such as a command unit, a VIP, or war supplies, is located at the center of the formation and users surround it while maintaining a predefined distance throughout the operation. The purpose of this operation is to protect the important resources from enemy forces and convoy it safely to a target point. Each user is assigned a responsible area to perform this mission and the user's movement is constrained by the assigned area. In our experiment, there are four pre-assigned patrol boxes in which two user nodes operate and stay inside during the simulation.

In the SR (search and rescue) mobility model, user nodes search a defined operational area for an asset with unknown location. One of the most important considerations in a search operation is that a given responsibility area can be covered as much as possible to accomplish an assigned mission efficiently. To meet this requirement, the responsibility area is uniformly divided into several sub-sectors. The number of sub-sectors is generally equal to the number of available users. Each user assigned to an individual sub-sector to search and rescue targets. User nodes start to search from initial points where the network is fully connected, and follow paths which are predefined to cover the given search area. The purpose of this operation is to search or rescue some targets such as mines, lost friendly forces, etc. The performance of an SR operation depends on the effective use of limited resources. For effective deployment of users in this operation, users need to be directed by an operational plan. First, each user node travels through predefined target points. This enables users to uniformly cover the responsibility area without wasting limited resources by duplicated deployment of users. The SR mobility model is the least random movement among those mobility models used in this study.

III. Experimentation and Results

In order to evaluate the performance of the agent location optimization model, we use a simulation model to evaluate the network performance for a set of randomly generated problems of a variety of sizes and configurations (a complete description of the simulation model, the model verification and experimentation is given in [4]).

The results reported here were generated using the following experimental conditions:

	User Mobility Model	
	RW and SR	CD
User Nodes	5	8
Agent Nodes	3	8
Control Nodes	1	1
Enemies	3	3

The simulations using the RW and SR mobility models were run for 200 time steps and the simulations using the CD mobility model were run for 180 time steps. All simulations included 100 replications and common random numbers were used in the comparisons. The performance metrics in which we are interested include the average number of connected users (over the simulation run).

Table 1 gives the numerical results comparing the average number of connected nodes for the PAL and No PAL cases with different numbers of enemy nodes. The results clearly show that the PAL parameter increases the average number of connected users. Figures 1, 2, and 3 show how the numbers of connected users evolve over time for the PAL and No PAL cases using the RW, CD, and SR user mobility models, respectively. Clearly the PAL parameter cases dominate the No PAL parameter cases for all mobility models over all time steps.

IV. Conclusions

This paper put forth a new approach to optimization ad-hoc mobile networks for military tactical operations. A PSO is used as the optimizer due to the need for fast, reliable results. At each time step of the network the movements of autonomous agents are selected to maximize network connectivity. We use minimum hops as a primary metric with some secondary metrics according to the connectedness state of the network. The agents are deployed, not only in response to user movements, but also to anticipate future use by using the PAL construct. PAL disperses agents amongst users and users amongst agents to avoid duplication and inactivity of agents. We show, using three mobility models, the power of the PSO and the usefulness of the PAL approach.

References

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Table 1. Number of Connected Users Over Network Duration

Mobility	Num Enemy	No PAL	PAL	p-value
		Avg N_U	*Avg* N_U	
RW	0	3.850	3.970	0.006
	1	3.792	3.944	0.000
	2	3.672	3.819	0.000
	3	3.540	3.647	0.019
	Avg	3.714	3.845	
CD	0	6.456	7.400	0.000
	1	6.453	7.314	0.000
	2	6.420	7.213	0.000
	3	6.449	7.226	0.000
	Avg	6.445	7.288	
SR	0	3.702	4.401	0.000
	1	3.547	4.223	0.000
	2	3.379	3.999	0.000
	3	3.314	3.830	0.000
	Avg	3.486	4.113	

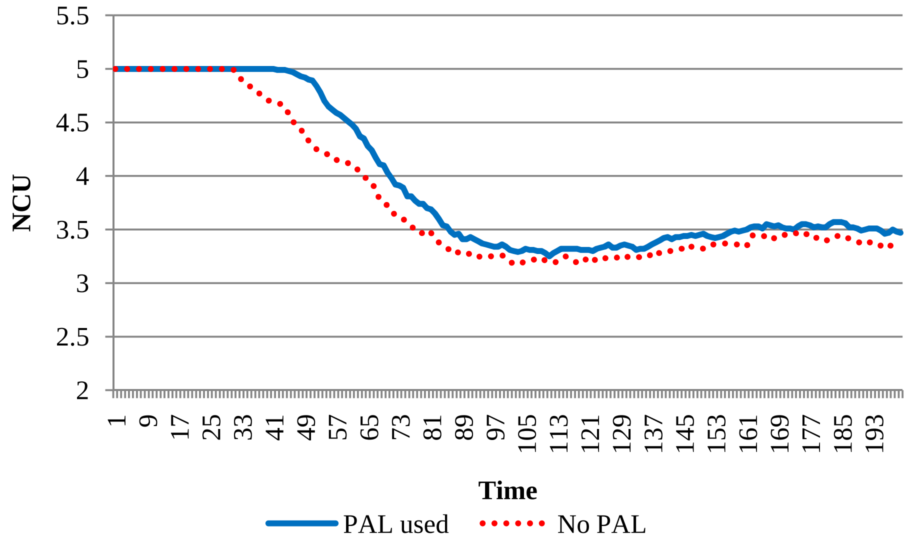

Figure 1. Comparison of PAL and No PAL (RW, 1E)

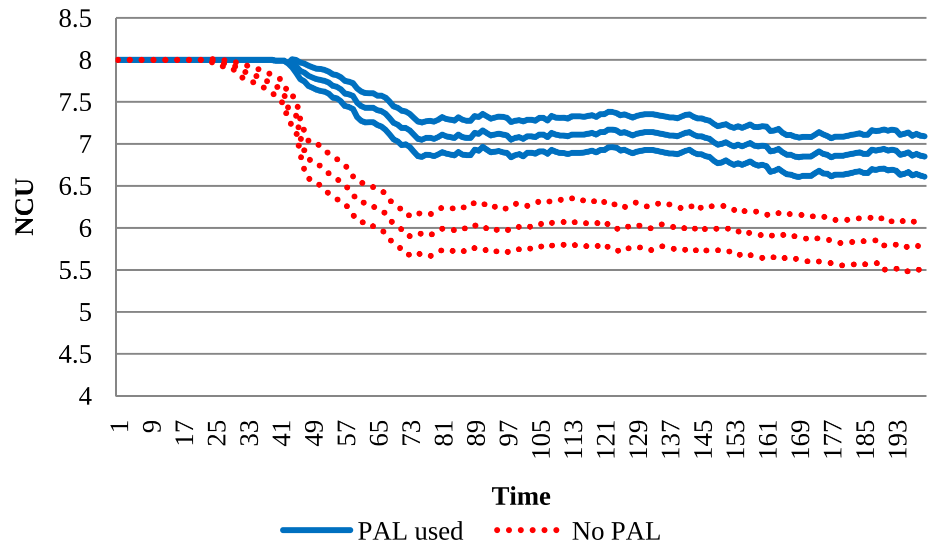

Figure 2. Comparison of PAL and No PAL (CD, 1E)

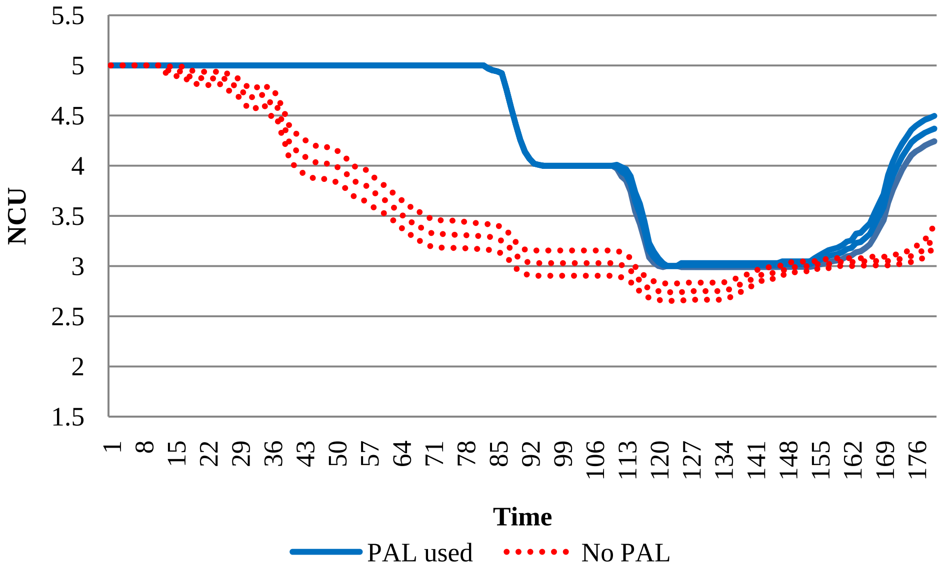

Figure 3. Comparison of PAL and No PAL (SR, 1E)