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A flocking-based approach to maintain connectivity in mobile wireless ad hoc networks

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ABSTRACT

Mobile ad hoc networks (MANET) have a set of unique challenges, particularly due to mobility of nodes, that need to be addressed to realize their full potentials. Because the mobile nodes of a MANET are free to move rapidly and arbitrarily, the network topology may change unexpectedly. This paper presents a decentralized approach to maintain the connectivity of a MANET using autonomous, intelligent agents. Autonomous agents are special mobile nodes in a MANET, but unlike other nodes, their function is to proactively prevent network bottlenecks and service problems by intelligently augmenting the network topology. To achieve this function without depending on a central network management system, autonomous agents are expected to dynamically relocate themselves as the topology of the network changes during the mission time. A flocking-based heuristic algorithm is proposed to determine agent locations. A computational study is performed to investigate the effect of basic flocking behaviors on the connectivity of a MANET.

1. Introduction

There are two types of wireless networks: infrastructure dependent and infrastructure-less networks. Infrastructure dependent networks, such as cellular networks, rely on base stations to route packets. Such networks are referred to as ‘single hop’ networks, as information is sent from the transmitting node to a base node (e.g., tower), then onto the receiving node. Routing is simplified in an infrastructure dependent network since a single central location keeps track of node locations and handles routing protocol. Infrastructure-less ad hoc networks have no central base station to relay data packets. Instead, each node is capable of routing and retransmitting data packets. Such a network is sometimes referred to as a ‘multi-hop’ network [16] as packets may be routed through several nodes before reaching their destinations. Nodes in a multi-hop network must be more intelligent than their infrastructure dependent counterparts as routing and resource management functions are distributed over the network.

Mobile wireless ad hoc networks (MANET) are instantaneous, autonomous multi-hop networks that provide service to users wherever and whenever the service is needed. Development time and cost of MANET are also relatively low compared to infrastructure dependent networks. Because of the relative ease with which MANET can be established, the technology has found use in situations where establishing an appropriate network infrastructure would be cost or time prohibitive, such as in military, emergency, or search and rescue operations. MANET also have the potential to create ubiquitous communication networks by seamlessly interconnecting thousands of devices [1,5,21].

The flexible nature of MANET, particularly mobility of nodes, brings a set of unique challenges that need to be addressed to realize their full potential. Because mobile nodes in MANET are free to move rapidly and arbitrarily, the network topology may change unexpectedly. The channel capacities of wireless links are limited and depend on the distance between nodes and environmental factors. Therefore, unexpected network bottlenecks may occur as the network topology and link capacities dynamically change over the time. In addition, certain devices may have limited power and processing capability. All these challenges may impair the performance of MANET.

Several approaches have been proposed in the literature to address the problems in MANET due to unpredictable node movements. One of the major problems is the accessibility of the centralized network services used by all nodes when the network is disconnected. This problem can be addressed by replicating network services [25] or critical data [11] at multiple nodes and dynamically deploying these nodes to disconnected partitions of the network. Another problem is the delivery of data packets across disconnected network partitions. In the literature, special agent nodes are proposed to address this problem [6,27]. These agent nodes can buffer packets until their destination nodes are

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reachable. When agent nodes are connected to a network partition, they deliver their payload. Alternatively, several papers [8,15] propose network topology control by modifying node trajectories or power levels [13,24].

There has been very limited work in the literature to improve network connectivity in MANET through mobile agents. For example, Ou et al. [20] propose special relay nodes that can adjust their locations to assist disconnected network partitions. Chadrashekar et al. [4] define the problem of achieving connectivity in disconnected ground MANET by dynamically placing unmanned air vehicles (UAVs) which function as relay nodes. Zhu et al. [28] also propose using UAVs equipped with communication capabilities to provide services to ground-based MANET. Recently, Hauert et al. [9] propose the deployment of a swarm of UAVs for search and rescue missions. During a mission time, UAVs are expected to maintain direct or indirect connection to their base-station through the ad hoc network that they form. Recently, Konak et al. [12] and Dengiz et al. [7] propose a MANET management system to improve MANET connectivity using agent nodes managed by a centralized network management system. In this MANET management system, a particle swarm optimization algorithm is proposed to dynamically determine agent deployment decisions by assuming that the global state of a network is available, and agent deployment decisions can be communicated to agents at all times.

As briefly summarized above, the current research on improving network performance and connectivity in MANET through auxiliary nodes, which are called agents in this paper, assumes the existence of a central network management system. This central management system is assumed to be aware of the global state of the network and capable of communicating with agents at all times. However, this assumption is not realistic in many real-world MANET. The research in this paper takes a different direction and proposes autonomous agent nodes, each of which is capable of making deployment decisions independently without relying on a central network management system. The proposed approach is to devise a set of rules that are similar to the flocking rules [18,22] to create a group-flocking behavior from the individual behaviors of a set of autonomous agents. Recently, there has been increased interest in multi-agent flocking for automated control in sensor networks and UAVs (e.g., [2,10,14,19,17,23,26]). However, multi-agent flocking has not been previously applied to improve network connectivity in MANET.

2. Problem formulation and assumptions

Let $G(t) = (N(t), E(t))$ denote a MANET with node set $N(t)$ and edge set $E(t)$ at time t. Node set $N(t)$ includes two types of nodes: users ($U(t)$) and agents ($A(t)$). Users demand network services, and they are assumed to move freely. Agents are responsible for helping users experience the best network service possible by dynamically adjusting their locations. Edge set $E(t)$ depends on the locations of users and agents, their transmission ranges, as well as other environmental factors at time t. Given position $\mathbf{p}_i(t) = (x_i(t), y_i(t))$ and transmission range R_i of each node $i \in N(t)$, edge set $E(t)$ at time t is determined as follows:

$$E(t) = \{(i, j) : i, j \in N(t), i \neq j, d_{ij} \leq \min(R_i, R_j)\} \quad (1)$$

where $d_{ij} = \| \mathbf{p}_i(t) - \mathbf{p}_j(t) \|$ (it is assumed that $(i, j) \equiv (j, i)$, and $\| \cdot \|$ denotes the Euclidean norm of a vector).

The overall objective is to maximize the connectivity of users during a mission time by dynamically locating a set of agents in response to the changes in the network topology. Given network topology $G(t)$ at time t, let $Q(G(t))$ be the percent of the connected (directly or indirectly) user node pairs. If the mission time is sliced into T discrete time steps, and given that agent i can travel a maximum of V_i unit distance in a time step, the overall problem can be expressed as follows:

Problem Agent:

$$Max \quad Q = \frac{1}{T}\sum_{t=1}^{T} Q(G(t))$$
$$\|\mathbf{p}_i(t) - \mathbf{p}_i(t-1)\| \leq V_i \quad \forall i \in A(t), t = 1, \ldots, T$$

Although Problem Agent is useful for describing the overall optimization problem, it is not practical to be used in real-world MANET for several reasons. First of all, Problem Agent assumes an implicit centralized network management system that is aware of the global state of the network (i.e., $G(t)$ is known by all agents) and that can communicate with all agents at all times. These assumptions may hold for some cases, but they are not realistic for many real-world MANET. More importantly, the future locations of users are not known when the deployment decision is made at any time t. Therefore, Problem Agent represents the theoretical best case of what can be achieved in the discrete time domain. In addition, Problem Agent is a non-linear mixed-integer programming problem, which is very difficult to optimally solve with limited CPU resources available to agent nodes. Furthermore, deployment decision should be made in very short time intervals.

The overall objective of the proposed flocking-based heuristic is to dynamically determine the best possible locations of autonomous agents and deploy them accordingly to maximize MANET connectivity: (i) in the absence of a centralized network management system; (ii) without complete and up-to-date information about the global state of the network; and (iii) with inadequate computing resources or limited time to carry out computationally expensive calculations. This paper proposes a decentralized approach based on the concepts from swarm intelligence, particularly based on the earlier work on flocking agents [22]. In the proposed agent deployment approach, agents use simple rules to determine their new locations as the topology of the network randomly changes. Preliminary results from a simulation study to determine the effects of agent level behaviors on the global network connectivity are reported. In addition, the performance of the proposed flocking-based heuristic is compared to a quadratically constrained mixed-integer programming approach.

3. Proposed approach

Flocking is a collective behavior of independent but interacting agents. Early work on flocking and swarm theory focused on mimicking realistic movements of flocking animals. Reynolds [22] introduced three basic rules that achieved the first simulated flocking in computer animations as follows:

- cohesion: attempt to stay close to nearby flockmates.
- separation: avoid collisions with nearby flockmates.
- alignment: attempt to match velocity with nearby flockmates.

In Reynolds's model, each agent can make independent decisions to maintain the flock. In addition, it is assumed that individual agents have no knowledge of the wider arrangement of other agents, and instead they are only aware of those agents in their immediate vicinity. The problem studied in this paper is quite different than the basic flocking behavior. Therefore, these basic flocking rules are redefined to maintain the connectivity of users.

Let vector $\mathbf{v}_i(t) = (vx_i(t), vy_i(t))$ denote the velocity of agent i at time t. Velocity vector $\mathbf{v}_i(t)$ represents the direction and the distance that agent i intends to move between times t and $t+1$, and the