

Intelligent Backbone Swarms for scalable, disruption tolerant wireless networking

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ABSTRACT

In this paper, we propose a swarm intelligence strategy for constructing a mobile backbone multicasting network which leads to improved scalability and connectivity compared to conventional flat networks. The strategy combines a simple clustering technique and On Demand Multicast Protocol (ODMRP). Also we show benefits of the mobile backbone network through a simulation study.

1. Introduction

This paper applies distributed optimization schemes in a real-world application context characterized by a “swarm” of interacting nodes. The specific characteristics that differentiate this problem from traditional “swarm intelligence” applications are that: each node can act only on a subset of the independent variables in the objective function and that individual nodes may need to be in constant motion (e.g., in the case of airborne vehicles) and therefore they need ways of maintaining a suboptimal solution in spite of this movement.

With advances in wireless ad hoc communications, robotics and micro-flyer technology, it will soon be possible to organize teams of small unmanned ground, sea and airborne vehicles and to launch complex missions that comprise several such teams. The typical application scenario is a disaster area that requires the intervention of police, firemen, paramedics etc, but where the unfriendly environment bars direct access. In this environment it is necessary to deploy a “backbone” swarm that supports communications among the various teams. The backbone swarm operates in a completely distributed, autonomous manner, establishing a communications network between the rescue teams and all critical fixed and mobile sensors and actuators in the disaster area. Multicasting, i.e., the transmission of messages or streams from one source

to one or more teams, is the prevailing communication primitive in swarming scenarios, as operational granularity is a team or group in most cases.

One impeding factor in the deployment of large scale swarm-based systems lies in the limited scalability of ad hoc communication system. It has been shown theoretically and experimentally that the capacity of a mobile ad hoc network (MANET) declines rapidly toward zero as the size of the network increases even under optimal conditions. Thus, a “flat” ad hoc network has an inherent scalability problem. The conventional solution is to resort to hierarchical structures. The backbone swarm can help establish a mobile, hierarchical network architecture that introduces extra capacity (via separate radios) and enhances throughput performance.

In emergency ad hoc networks connectivity is even more critical than capacity. Nodes can be partitioned into a few sub-networks due to physical obstacles, mobility, node failures and etc. A properly self-configuring mobile backbone swarm with airborne nodes equipped with long range radios can help overcome these problems as well. These mobile backbone nodes are equipped with two radios: one is a conventional ad hoc radio to communicate with non-backbone nodes and the other is a long range radio to communicate with other backbone nodes. Long range radios, however, may have less bandwidth than short range radios (depending on the range). Thus, the backbone links in some cases may be adequate to transmit controls, but not to carry high volumes of information, e.g., video streams. To this end, we will exploit the fact that some applications are “delay tolerant” and “disruption tolerant”: namely, the nodes in the backbone may “ferry” content around as “data mules”. The choice of transmitting directly or physically carrying data to the destination will vary from application to application. Selecting the best strategy for immediate versus delayed

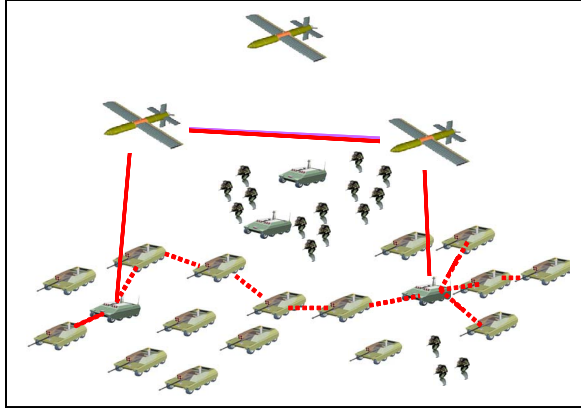


Figure 1. A typical backbone swarm. The backbone network consists of aerial nodes and selective ground nodes. The solid line shows a communication path through the backbone network.

delivery is another aspect of “swarm intelligence”, as it requires transmission and motion coordination.

In this paper, we investigate mobile backbone swarm strategies in which the swarm can autonomously self-configure in a backbone topology providing multicast communications among mobile teams. This work advances the state of the art in several directions. Previous research in this area has addressed the question of optimal backbone deployment under central control such as a team of UAVs teleguided from a central control station with full knowledge of asset layout and traffic requirements. Here, the backbone swarm is completely autonomous. It must learn about the existing network independently by “interrogating” nodes and monitoring traffic. Moreover, it must learn about potential connectivity breaks and repair them. We use advanced, distributed clustering techniques and optimization methods to attack this problem based on the swarm intelligence. We have also developed “learning” techniques such as “reactive” strategies that enable swarm elements to quickly acquire knowledge of the environment (e.g., the layout of a subway network, the blueprint of a chemical plant under attack, etc) and to construct a model of node mobility so that connectivity failures can be accurately predicted. Work is in progress to develop efficient strategies for swarm motion combined with data ferrying.

Usually, a swarm of unmanned, intelligent vehicles is charged with several other functions besides communications. For example, the airborne vehicles

carry video cameras and other types of sensors for scouting missions etc. In our task, for simplicity we assume that our swarm is exclusively dedicated to communications. Moreover, in several swarm scenarios, low energy operation is a must. In our case, as we will consider airborne vehicles, we will assume that the energy required for communications will be a small fraction of that required for vehicle propulsion.

2. Overview of ODMRP

On Demand Multicast Routing Protocol, ODMRP [1], is a popular ad hoc multicast used in very mobile systems. ODMRP introduces the concept of *forwarding group*: a set of nodes responsible for forwarding multicast data forming a “mesh fabric” for each multicast group rather than a tree as in conventional protocols. The forwarding mesh is much more robust than the tree in high mobility situations.

Similar to on-demand unicast routing protocols, Query and Reply phases make up the protocol. While a source has packets to send, it periodically floods a control packet, called Join Query. The periodic floods refresh membership information and update the forwarding mesh. Namely, upon receiving a non-duplicate Join Query packet, every node in the network stores the upstream node address (i.e., reverse path learning) into the route table and rebroadcasts the packet to its neighbor nodes.

When the Join Query packet reaches a multicast receiver, the receiver creates and broadcasts a Join Reply to its neighbors. This Join Reply packet is propagated all the way back to the source following the learned reverse path. Nodes on the reverse path become the forwarding group, i.e. have the Forwarding Group Flag set. During the data phase, Forwarding Group nodes rebroadcast the packets belonging to the associated Membership Group. For example, if the group consists of only two nodes (sender and receiver), ODMRP will flag nodes along the shortest path as forwarding nodes. These nodes will then deliver packets from source to destination virtually implementing unicast routing as a special case of multicast.

3. Mobile backbone dynamic configuration

As backbone nodes are moving and can fail, dynamic backbone maintenance is essential. In earlier work [4], we presented an efficient backbone election/maintenance algorithm that dynamically reconstructs the backbone network with changing topology. Our approach has been to deploy redundant backbone capable nodes that can communicate with each other. When a backbone node is destroyed or moved out of an area, a new backbone capable node will substitute it. Backbone nodes are elected using the Random Competition-based Clustering (RCC) algorithm [4]. RCC is a distributed, K -hop clustering algorithm based on “first-declaration wins” rule [5]. The main idea of RCC is that any backbone capable node can initiate a cluster formation by broadcasting a packet to claim itself as a cluster head (i.e., backbone node) if there is no other backbone node within K -hop distance. The first node that proclaims to be a backbone node will be accepted as the cluster head by its neighbors. The neighbor nodes after hearing the declaration become *spare* backbone capable nodes (i.e., member nodes in the cluster).

ODMRP can be extended to support the mobile backbone network in several possible ways. In the approach that we adopt, the backbone nodes re-broadcast *Join Query* messages on two interfaces (normal and backbone) while ordinary nodes forward *Join Query* only on the normal radio interface. Each backbone node maintains the outgoing interface index to forward data packets besides forwarding flag and membership information. As each receiver chooses the shortest path to the source and backbone nodes have higher radio range than normal nodes, a remote member is more likely to choose a path through backbone nodes. Thus, implicit hierarchical multicasting is realized.

4. Simulation

Here, we provide a preliminary evaluation of the performance gains offered by the swarming backbone using ODMRP. We use the QualNet simulation platform [2], properly extended to support mobile backbone nodes. The transmission ranges of ground and backbone radio are 376 and 800 meter respectively. As one of our interests is scalability, we use a large-scale network where 500 mobile nodes are randomly placed within $3000 \times 3000 \text{ m}^2$. CBR (Constant-bit rate) application, UDP, ODMRP, IEEE 802.11 DCF MAC and two-ray channel models are used for simulation runs. We assume the total

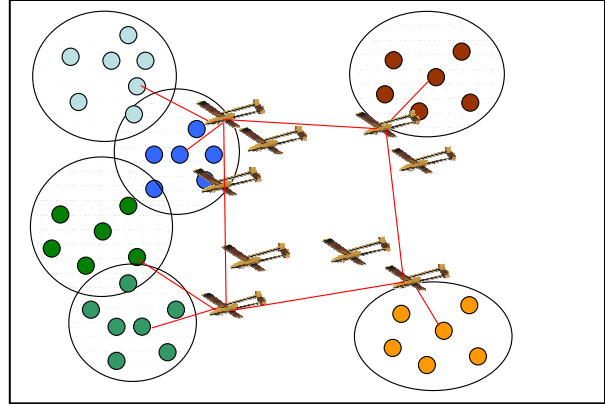


Figure 2. Group mobility scenario. Nodes are organized into teams and show coordinated motion. The backbone network connects islands of networks.

bandwidth is 2Mbps and the bandwidth is split equally between the two radio channels when the backbone network is deployed. We investigate two scenarios. The first scenario is the individual mobility scenario in which nodes in the network move independently. The second is the group mobility scenario (illustrated in Figure 2) in which network nodes show a coordinated motion, i.e., nodes are organized into groups and members in a group move together. For the mobility model, we use the Random Waypoint model in the first scenario and the Reference Point Group Mobility model [7] is employed in the second scenario. In both simulation scenarios, the multicast group has a single source and 30 receivers. The source transmits with a constant rate of 1Kbytes/sec. Results are averaged value of 10 simulations runs.

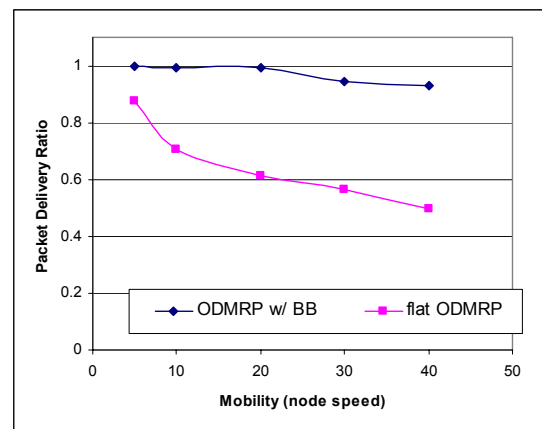


Figure 3. Delivery ratio versus node mobility in the individual mobility case.

Figure 3 shows the delivery ratio of ODMRP with/without the backbone network in the individual

mobility scenario. In this scenario, most of the nodes in the network are connected to each other. As clearly shown in the figure, mobile backbone nodes improve the delivery ratio in mobile scenarios. The longer range reduces the total average hop count and thus lowers the chance of packet drop due to wireless mobility.

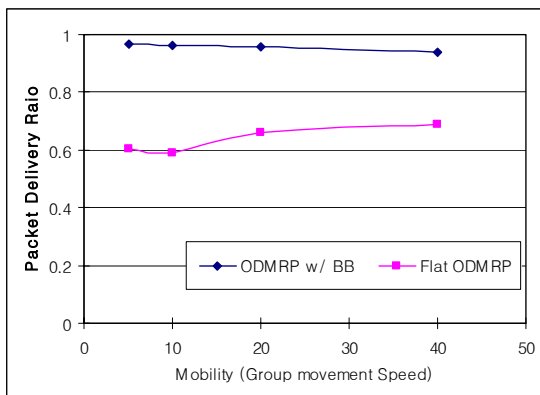


Figure 4. Delivery ratio versus node mobility in the group scenario.

Figure 4 shows the delivery ratio of ODMRP with/without the backbone network in the group mobility scenario. The scenario leads to non-uniform distribution of nodes and the network which is connected in the individual mobility scenario becomes disconnected without the backbone links. The delivery ratio is only around 60% even when mobility is very low. The backbone network shows a significant performance improvement also in this group mobility scenario since its long haul radio expands the coverage. Interestingly the delivery ratio in the flat ODMRP network increases as mobility gets higher. The simple explanation is that with higher mobility the disconnected components can more easily move to a position where they become reconnected.

Regardless of motion modality, the mobile backbone swarm provides a dramatic improvement. However, as ground groups become progressively separated by larger and larger distances, the backbone links must “stretch” and trade bandwidth for range. In other words, the backbone capacity becomes “thin” and can carry only control and light data information. It cannot carry high volume transfers and high data rate streams (e.g., video, imagery, terrain info, etc). This suggests the use of “disruption tolerant” networking concepts. High volume data can be cached in the nearest backbone node. As backbone nodes constantly move, the backbone node with the cache

eventually becomes “high speed” connected to the destination group and can deliver the data. This mode of operation works only if the application is “delay tolerant” (e.g., terrain information; background video, etc). Moreover, this procedure requires “swarm intelligence” in download and motion coordination.

5. Conclusion

In this paper, we have investigated mobile backbone swarm strategies in which swarm intelligence allows autonomous self-configuration providing multicast communications among mobile teams. Simulation results showed that the adaptive mobile backbone significantly improves performance. Swarm intelligence can be further exploited to support “delay tolerant” applications.

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