Analysis of Topological Characteristics of Unreliable Mobile Wireless Ad Hoc Network

Saurabh Bagchi, Serdar Cabuk, Longbi Lin, Nipoon Malhotra, Ness Shroff

Electrical and Computer Engineering Department, Purdue University
465 Northwestern Avenue, West Lafayette, IN 47907.
Phone: 765-494-3362. Fax: 765-494-2706.
Email: {sbagchi, scabuk, llin, nmalhot, shroff}@purdue.edu

Abstract

The paper presents a simulation-based study of topological characteristics of a mobile wireless ad-hoc network with unreliable nodes. The characteristics studied are connectivity, coverage, maximum inter-node distance and node degree. Knowledge of these characteristics aids in the design of new distributed protocols as well as in predicting the performance and robustness of current protocols executing on the network. The paper presents intelligent mobility algorithms which aim to achieve desired levels of the output parameter values. The environment is unreliable with nodes prone to failures, in either permanent or transient manner. The nodes also have constraints on their transmission ranges arising from constraints on the power consumption. In this paper, we study the behavior of the output measures with increasing number of nodes in the topology and find that coverage is the primary determinant of the number of nodes. The behavior is studied successively under failure-free conditions, and with node failures. The results bring out cutoff points for ratio of permanent to transient failures and mean time to failure (MTTF) beyond which the QoS for the output measures degrades sharply. We also present a theoretical derivation of the sufficient condition for connectivity and coverage in the network and validate the result through simulation.

Keywords: ad-hoc mobile wireless network, simulation-based study, node failures, connectivity, coverage, and diameter.

Declaration: This work has been cleared through the affiliations of each author.

1 Introduction

A mobile ad hoc network is an autonomous system of mobile hosts connected by wireless RF links. There is no static infrastructure such as base stations. If two hosts are not within radio range, all message communication between them must pass through intermediate hosts which double as routers.

Sensor networks are a particular class of wireless ad hoc networks in which the nodes have micro-electro-mechanical (MEMS) components, including sensors, actuators and RF communication components. Sensor nodes are randomly dispersed over the area of interest and are capable of short-range RF communication (≈ 100 ft) and contain signal processing engines to manage the communication protocols and for data processing. The individual nodes have a limited processing capacity, but are capable of supporting distributed applications through coordinated effort in a network that can include hundreds or even thousands of nodes. Sensor nodes
are typically battery-powered and since replacing or recharging batteries is often very difficult, reducing energy consumption is an important design consideration for sensor networks. Since the transmission range of a node is proportional to the square root or fourth root of the transmitting power, the range of a sensor node is constrained in most deployments.

In many applications of wireless ad hoc networks, the hosts are mobile which complicates analysis of network characteristics because the network topology constantly changes. The sensor nodes are likely to be more failure-prone than traditional wired, larger scale devices and will typically be deployed for extended periods of time. Since replacing the power source is considered difficult due to the placements of the sensor nodes, therefore exhaustion of battery resources can be taken as permanent node failures. In addition, we also need to consider transient node failures. The primary cause of this will be interference whereby a jamming effect is encountered and all communication channels from the node are rendered unusable. For such transient failures, the failure pattern cannot be clearly defined and will depend on the communication pattern and topology of the nodes. The links in a sensor network are also prone to failures. Transient link failures are a function of the relative motion and relative distance of the nodes which are the end-points of the link. The changing topology because of mobility and failures makes analysis of the network characteristics challenging.

The network characteristics considered in the study are connectivity, coverage, diameter, and node degree. These characterize the network’s utility in running useful higher layer protocols. Complete connectivity in the network implies communication is possible between any two pairs of nodes. Coverage indicates the percentage of the sensor field that can be sensed by at least one node and therefore, properties of the area can be known. Diameter is the maximum number of hops between any two nodes and the product of diameter and per hop latency serves as the upper bound on the communication delay in the network. The average degree of a node in the network is an indicator of the robustness of the network to node and link failures. Also a higher node degree provides for load balancing the communication from the node across multiple paths.

To harness the power of the massive numbers of sensor nodes for useful applications requires a middleware architecture that provides higher level primitives, such as querying, clustering, and monitoring. The middleware protocols on sensor nodes are of two basic types – (i) the aggregation type where the nodes send information to an elected leader, which performs data aggregation and processing; (ii) the homogeneous kind where each node plays an identical role, such as in clustering of sensor nodes based on proximity. The safety, liveness and performance of these protocols are dependent on the characteristics of the underlying network. There have been theoretical studies that have looked at a single parameter (connectivity in [10]) or two parameters (connectivity and degree in [11]) in a static wireless environment. However, these studies have not considered the effect of mobility (or done so for asymptotic cases of number of nodes), and transient and permanent failures on the network characteristics. Also, intelligent mobility patterns that can be employed to improve the network characteristics have not been studied in such environments.

There exists a volume of work on the low-level routing protocols in ad-hoc wireless networks. The fundamental premise of the routing protocols, such as OSPF [1] and RIP [2], is to find the shortest distance
between any pair of nodes. However, characteristics of ad-hoc wireless networks (dynamic, low processing overhead tolerable for route calculation) have motivated new routing protocols, such as DSDV [3] and TORA [4]. Energy-aware routing to minimize the energy consumption in the sensor nodes has been an active area of study [5]. More recent work has proposed that minimizing energy in routing protocols may not be optimal for network lifetime or long-term connectivity of the network [6]. In our work, we are not concerned with the routing protocol in use. We assume that the system has the most appropriate routing protocol in place.

In the paper, we present a theoretical derivation of the sufficient condition for connectivity and coverage in a two-dimensional grid of nodes which can move and can fail. A previous study [14] had considered these properties in the case of random node placements and a second study [15] had studied them in the case of stationary nodes with failure probabilities. In this study, we present extensive simulation results that show how many nodes are required to satisfy given constraints on the parameters of interest. A previous study had looked at network connectivity with mobility in a two-dimensional ad-hoc wireless network [7]. However, connectivity does not capture all the performance impact on the higher-level protocol, and a combination of connectivity, coverage, inter-node distance and degree is more representative. We believe this is the first study to evaluate a combination of network characteristics and investigate the effect of transient and permanent host failures on them. We propose a suite of intelligent mobility algorithms for the nodes that can be used to optimize the combination of these network characteristics to meet a user specification.

The rest of the paper is organized as follows. Section 2 gives the system model for the ad hoc wireless network. Section 3 presents the measures of interest in the study, the failure model for node and link failures, and the intelligent mobility algorithms. Section 4 presents the derivation of the sufficient condition for two parameters (100% connectivity and 100% coverage) in the presence of node mobility and node failures. Section 5 presents the problem statement for the simulation work, together with the assumptions, and details of the simulation model. Section 6 provides results from the simulation and our conclusions from them. Section 7 concludes the paper.
References