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Modelling and performance analysis of multi-hop ad hoc networks

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ABSTRACT

Mobile ad hoc networks are becoming very attractive and useful in many kinds of communication and networking applications. Due to the advantage of numerical analysis, analytical modelling formalisms, such as stochastic Petri nets, queuing networks and stochastic process algebra have been widely used for performance analysis of communication systems. To the best of our knowledge, there is no previous analytical study that analyses the performance of multi-hop ad hoc networks, where mobile nodes move according to a random mobility model in terms of the end-to-end delay and throughput. This work presents a novel analytical framework developed using stochastic reward nets for modelling and analysis of multi-hop ad hoc networks, based on the IEEE 802.11 DCF MAC protocol, where mobile nodes move according to the random waypoint mobility model. The proposed framework is used to analyse the performance of multi-hop ad hoc networks as a function of network parameters such as the transmission range, carrier sensing range, interference range, number of nodes, network area size, packet size, and packet generation rate. The proposed framework is organized into several models to break up the complexity of modelling the complete network, and make it easier to analyse each model as required. The framework is based on the idea of decomposition and fixed point iteration of stochastic reward nets. The proposed models are validated using extensive simulations.

1. Introduction

Traditional wireless communication networks, namely cellular and satellite networks, require a fixed infrastructure over which communication takes place. Accordingly considerable efforts and resources are required for such networks to be set up, before they can actually be used. In cases where setting up an infrastructure is a difficult or even impossible task, such as in emergency/rescue operations, military applications or disaster relief, other alternatives need to be devised. Mobile ad hoc networks (MANETs) are stand alone wireless networks that lack the service of a backbone infrastructure [1]. They consist of a collection of mobile nodes, where the mobile nodes act as both sources and routers for other mobile nodes in the network. A node can send a message to another node beyond its transmission range by using yet further nodes as relay points operating as routers. This mode of communication is known as wireless multi-hop. All nodes of the network have the same capabilities and no base stations or central access points need to be involved in the data exchange. In some instances, a gateway node may be presented in an ad hoc network which may allow the nodes to communicate with an external network, e.g. the Internet.

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In MANETs, each node is supplied with an antenna that allows it to transmit and receive information from the other nodes. The antenna can radiate and receive within a certain radius, called the transmission range. The radius is determined by the transmission power. When a node transmits to another node, its transmission can be heard by all nodes that lie within the transmission range. The higher the transmission power, the larger the number of nodes that can be reached in a single transmission, but also the higher the amount of the interference that may be experienced. The network is formed as soon as one of the nodes expresses a wish to exchange information with one of the other nodes (unicast) or with more than one node (multicast). Such networks were initially designed for use in the military and emergency relief applications. Lately, the ad hoc network model has been proposed in many other applications [1].

Mobile ad hoc networks share many of the properties of wired and infrastructure wireless networks, but also have certain unique features which come from the characteristics of the wireless channel. Nodes in MANETs are free to move, thus the network topology may change rapidly and therefore, nodes need to collect connectivity information from other nodes periodically. One implication of this is an increased message overhead in collecting topology information. Mobility is a crucial factor affecting the design of MANET protocols, including Medium Access Control (MAC), Transmission Control Protocol (TCP), and routing protocols.

Mobile ad hoc networks are becoming very attractive and useful in many kinds of communication and networking applications, due to their efficiency, simplicity (in installation and use), relatively low cost, and availability. It is to be noted that most of the research that has studied the performance of MANET was evaluated using Discrete event simulation (DES) utilizing a broad band of simulators such as NS2 [2], OPNET [3], and GloMoSim [4]. The principal drawback of DES models is the time and resources needed to run such models for large realistic systems, especially when results with high accuracy (i.e. narrow confidence intervals) are required. Due to the advantages of numerical analysis, analytical modelling formalisms, such as stochastic Petri nets and stochastic process algebra, have been used for performance analysis of communication systems. Compared to measurement and simulation methods, analytical modelling is a less costly method [5,6]. It generally provides the best insight into the effects of various parameters and their interactions [5,7]. Hence, analytical modelling is the method of choice for a cost effective evaluation of communication systems.

Multi-hop ad hoc networks are too complex to allow analytical study for explicit performance expressions. Consequently, the number of analytical studies of this type of network is small [8–18]. In addition, most of these studies have a number of drawbacks, which can be summarized as follows:

1. Most of analytical research in MANET supposes that the nodes are stationary (no mobility), or the network is connected all the times, to simplify the analysis [8–18].
2. In order to be mathematically tractable, most analytical studies suppose that the nodes in the network area are uniformly or regularly distributed [9,11,12,16].
3. Some of the research is restricted to the analysis of single hop ad hoc networks [8–10,13].
4. The impact of the interference range on the performance of multi-hop ad hoc networks is either ignored or largely simplified [8–18].
5. To simplify the analysis, most studies investigate MANETs in the case of a saturated traffic load (i.e. at all times every node has a packet to send) or finite load traffic, not in both cases [8,11,12,14].
6. For computing the expected length (number of hops) of paths in multi-hop ad hoc networks, inaccurate approximate methods have been used [14–16] (see Section 2 for more detail).
7. To reduce the state space of the analytical models of MANETs, most of the research is macroscopic (dynamics of actions are aggregated, motivated by limit theorems) [8–14,16].

To the best of our knowledge, there is no analytical study that analyses the performance of multi-hop ad hoc networks based on the IEEE 802.11 MAC protocol, where nodes move according to a random mobility model, in terms of the end-to-end delay and throughput. This work presents an analytical framework, developed using the Stochastic Reward Net (SRN) [19] and mathematical modelling techniques, for the modelling and analysis of multi-hop ad hoc networks based on the IEEE 802.11 DCF MAC protocol where nodes move according to the random waypoint mobility model (RWPMM). The proposed framework is used to analyse the performance of multi-hop ad hoc networks as a function of different parameters such as transmission range, carrier sensing range, interference range, node density, packet size, and packet generation rate. Although the proposed framework is specific to a certain type of a MAC protocol and random mobility model, it can be adapted for use with other MAC protocols and mobility models. The proposed methodology could also be used to analyse other type of networks.

To present an approach for the modelling and analysis of large-scale ad hoc network systems, there are two requirements in advance. First, the model should be detailed enough to describe some important network characteristics that have a significant impact on the performance. Second, it should be simple enough to be scalable and analyzable. It is clear that these two requirements are potentially contradictory. To fulfil these two requirements, to model multi-hop ad hoc networks using stochastic reward nets, we cannot construct a model for all nodes in the network by placing a model for each node into it one by one, because we will face the state explosion problem. Alternatively, in the same way as introduced in previous studies [8–18], by exploiting the large amount of symmetry in multi-hop ad hoc networks in order to simplify the analysis, only the behaviour of a single hop communication between any two nodes in the network needs to be modelled. Then, the single hop