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Throughput analysis in mobile ad hoc networks with directional antennas ☆

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A B S T R A C T

A major obstacle stunting the application of mobile ad hoc networks (MANETs) is the lack of a general throughput analysis theory for such networks. The available works in this area mainly focus on asymptotic throughput study (order sense) in MANETs with omnidirectional antennas or directional antennas. Although the order sense results can help us to understand the general scaling behaviors, it tells us little about the exact achievable throughput. This paper studies the achievable throughput of a MANET where each node is equipped with a directional antenna of beamwidth θ for transmission. A generalized two hop relay scheme with packet redundancy f is adopted for packet routing. Based on the Markov chain and automatic feedback theory, we explore a general theoretical framework that enables the achievable throughput analysis to be conducted for a directional antenna-based MANET. Based on the results of the achievable per node throughput, we further explore the throughput optimization problem for a fixed beamwidth θ and determine the corresponding optimal setting of f to achieve the optimal throughput. Numerical studies are also conducted to demonstrate the efficiency of these models.It shows that the maximum achievable throughput obtained from our theoretical framework matches nicely (with at most 7% difference) with that obtained from simulation under a realistic model.

1. Introduction

A mobile ad hoc network (MANET) is a collection of self-autonomous mobile nodes that communicate with each other via peer-to-peer wireless links with no preexisting infrastructures. The MANETs are of great importance in many key applications for their promising features of rapid deployment and robustness. However, a general throughput analysis theory for MANETs has remained an open problem, and it is expected that such a theory can provide valuable insight into improving the design and performance of future wireless networks [1,2]. By now, a lot of work has been done on the throughput analysis study of wireless ad hoc networks with omnidirectional antennas or directional antennas.

In terms of achievable throughput in the MANETs using omnidirectional antennas, the problem has been studied under various mobility models. Grossglauser and Tse [3] showed that under the i.i.d. mobility model, a MANET based on two hop relay routing scheme can stably support a $\Theta^2(1)$ per node throughput. Their result indicates that the per node throughput can be kept *constant* even as the number of nodes

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[2] In this paper, for two functions $f(n)$ and $g(n)$, we denote $f(n) = O(g(n))$ if and only if there exist positive constants c and n_0, such that for all $n \geqslant n_0$, the inequality $0 \leqslant f(n) \leqslant c\, g(n)$ is satisfied; $f(n) = \Omega(g(n))$ if and only if $g(n) = O(f(n))$; $f(n) = \Theta(g(n))$ if and only if both $f(n) = O(g(n))$ and $f(n) = \Omega(g(n))$ are satisfied.

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per unit area increases. Later it was proved that the $\Theta(1)$ per node throughput is also achievable in MANETs under the random walk model [4], the two-dimensional Brownian motions model [5] and the restricted mobility model [6], respectively. Perevalov and Blum [7] studied the throughput with delay constraints in MANETs using omnidirectional antennas. The tradeoff between throughput and end-to-end delay is further investigated in [8–12].

Many research efforts have been made to empirically investigate the throughput for wireless ad hoc networks using directional antennas. Ramanathan [13] simulated a 40 node network and showed that an improvement of up to 118% in throughput can be achieved by adopting directional antennas. Liu et al. [14] built a nine node testbed and showed that it is possible to improve the indoor network throughput by coordinating the orientations of the employed directional antennas.

The throughput of directional antenna-based wireless ad hoc networks has also been analytically studied in the literature. Spyropoulos and Raghavendra investigated the asymptotic throughput scaling behaviors of wireless ad hoc network for different directional antenna models and communication models in [15,16]. Based on the typical framework developed in [17], Yi et al. [18,19] assumed a *sender-based* protocol model and showed that under the considered network scenario the throughput improvement compared to the omnidirectional network is $2\pi/\sqrt{\alpha\beta}$ in random networks and is $4\pi^2/\alpha\beta$ in arbitrary networks, where α and β are the antenna beamwidths for transmission and reception, respectively. By introducing a new directional protocol model in [20], Li et al. provided an upper bound of $O\left(\sqrt{\log n/n}\right)$ and a lower bound of $\Omega\left(1\middle/\sqrt{n\log n}\right)$ on the maximum achievable throughput of random networks with multihop relay schemes, where n is the number of nodes randomly distributed in a disk network of unit area. The studies of network throughput improvement by using directional antennas have also been extended to flow networks [21], multi-channel wireless networks [22] and hybrid wireless networks with infrastructures support [23–25].

It is notable that the above works mainly focus on the throughput analysis of either MANETs with omnidirectional antennas or wireless ad hoc network with directional antennas, and to the best of our knowledge, the throughput analysis of MANETs with directional antennas is still an unexplored issue. Another common limitation of the above works is that they mainly explored the order sense behaviors of throughput. Order sense results, which often appear with approximation notations like O, Ω and Θ, correspond to the growth rate of the maximum achievable throughput when the number of node per unit area n tends towards a particular value or infinity. Although the order sense results can help us to understand the general scaling laws, they tell us little about the exact achievable throughput. In practice, the exact achievable throughput is of great significance for network designs. In this study, instead of deriving order sense results, we aim to analyze the exact achievable throughput which has a closed-form expression. Recently, Liu et al. [26,27] developed a framework to analyze the achievable throughput of MANETs using omnidirectional antennas. They studied in [26] the achievable throughput of MANETs adopting a general two-hop relay with packet redundancy limit f (2HR-f) for packet routing, and they further explored in [27] the impact of transmission power control on the achievable throughput there. In this paper, we study the achievable throughput of a MANET in which each mobile node is equipped with a directional antenna for transmission and the general 2HR-f algorithm is adopted for packet routing.

The main contributions of this paper are summarized as follows:

(1) We develop closed-form models such that throughput analysis can be conducted for any specified setting of antenna beamwidth θ and packet redundancy limit f, which cover those for MANETs with omnidirectional antennas as special cases.
(2) We then formulate the throughput optimization problem for a specified antenna beamwidth θ and any value of f, and also determine the corresponding optimal setting of f to achieve the optimal throughput of the specified θ.
(3) Extensive simulation studies are conducted to demonstrate the efficiency of these models and verify our theoretical results.

The rest of the paper is organized as follows. In Sections 2 and 3, we introduce the system models and routing algorithm adopted in our study, respectively. Section 4 presents the main results on achievable throughput and throughput optimization problem. The numerical results and associated discussions are provided in Section 5. We finally conclude this paper in Section 6.

2. System model

2.1. Directional antenna model

Directional antennas have the property of radiating electromagnetic waves more effectively in some directions than in others. In this paper, we consider that the directional antenna consists of a mainlobe which represents the main intended radiation directions. Sidelobes are ignored for the reason that they usually indicate radiation in undesired directions and the antenna gain in them is too small in comparison with that in the mainlobe [22]. *Beamwidth* is an important parameter to character the mainlobe and in this paper we refer the beamwidth to the half-power beamwidth, which is defined as the angle between the two directions in which the radiation intensity is one-half value of the maximum radiating direction. The antenna gain (in a given direction) is defined as the ratio of the radiation intensity in a given direction to the radiation intensity of an ideal isotropically antenna, whose radiation intensity is given by $\eta P_{rad}/4\pi$, where P_{rad} is the total radiation power over all directions and η is the antenna efficiency which is fixed to be 1 in this paper. In this paper, we consider two antenna models: a realistic antenna model and an ideal antenna model.

2.1.1. Realistic antenna model

For the realistic antenna model, we consider that the antenna gain is a function of the radiation angle ϕ with