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Simulation modeling and analysis of the hop count distribution in cognitive radio ad-hoc networks with beamforming

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ABSTRACT

Due to the spatial–temporal spectrum mobility in cognitive radio ad-hoc networks (CRAHNs), multi-hop communication paths among secondary users have to detour or even be disconnected to avoid interfering with primary users. Consequently, the hop count in CRAHNs shows distinguishing characteristics compared with those in conventional ad-hoc networks (AHNs). Although the influences of beamforming on the connectivity of CRAHNs have been studied in the literature, no research works on investigating the hop count in cognitive environment under the joined effect of beamforming have been conducted. In this paper, we model CRAHNs where SUs are equipped with directional antennas as geometric random graphs and then propose a framework for simulation analysis of the hop count distribution. Our proposed framework comprises of two components. The first one is an algorithm which finds all possible paths between two random secondary users selected as source node and destination node then returns the hop count of the shortest path between them by using the random values of node location and active state, antenna gain, and channel fading as input data. The second one is a methodology which returns the hop count distribution and connection probability of these two nodes from vast number of examined random network topology trials. We show that the hop count and the connectivity between two secondary users greatly depend on the number of antenna elements of directional antenna. Moreover, only a specific combination of direction antenna and beamforming scheme gives better performance than omnidirectional antenna. The observed results in this paper provide useful guidelines on designing and evaluating hop count based applications in CRAHNs with beamforming.

1. Introduction

Ad-hoc networks (AHNs), also referred as packet radio networks, are formed by a group of nodes that move freely and communicate with each other via wireless links [1,2]. The nodes in AHNs operate in a decentralized and self-organized manner without relying on any fixed infrastructure. The main advantages of AHNs are flexibility, low cost, and robustness which make them well suited for military activities, emergency operation, disaster recovery, large scale community networks, and small networks for interaction between meeting attendees or students in a lecture room. Generally, since the transmission

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ranges of all wireless nodes in AHNs are limited, each node operates not only as a host but also as a router, forwarding packets for other nodes in the networks that may not be within direct transmission range of each other. The hop count refers to the number of intermediate nodes through which data packets travel between source node and destination node. The analysis of the hop count characteristics in wireless AHNs is very important because it can be used in many applications such as (i) to estimate the packet delivery ratio of multi-hop path [3], (ii) to calculate the end-to-end delay if per hop delay is known [4], (iii) to determine the flooding cost and search latency during path discovery phase [5], and (iv) to analyze the path connectivity of two wireless nodes [6].

Because of the strong influences of hop count on the performance of wireless AHNs, there has been significant interest on analyzing the hop count features in wireless AHNs. More specifically, the authors of [7] estimate the hop count in three position based routing schemes, i.e. directional based routing, greedy routing, and most forward within radius (MRF) routing. It is shown that the number of transmissions needed to route a message from a source node to a destination node can be estimated with reasonable accuracy, especially when node density is high. A probabilistic analysis that captures the bounds on hop count from a given Euclidean distance between two nodes and vice versa in greedy least remaining distance (LRD) forwarding in wireless AHNs is presented in [8]. The authors conclude that the moments of one-hop distance progress are slowly varying functions of the distance to the destination, and can be considered nearly constant for a given node density and network size. From these results, the average hop count for a given Euclidean distance is obtained. Then, from the hop count, the average and bounds of Euclidean is derived. Details of this analytical approach and its applications are given in [9]. The relationship between the number of hops and the distance separating two nodes in uniformly distributed one dimensional and two dimensional wireless sensor networks is studied in [10]. For the one dimensional case, the authors give an exact recursive formula for the computation of various parameters while for the two dimensional case, they propose several approximations. Considering a connected network with Poisson randomly distributed wireless nodes, the authors of [11] presents a mathematical model of the expected number of hops between any two random nodes. Theoretical analysis for the expected number of hops in mobile AHNs where nodes move according to random waypoint mobility model and use a greedy routing approach called maxium hop distance (MHD) is given in [12]. The proposed theoretical analysis is validated for different network parameters such as node density, size of the network area, node transmission range. Instead of assuming a free space path loss wireless channel, the authors of [13] investigate the probability that two nodes separated by a known Euclidean distance are k-hop apart in wireless multihop AHNs subject to both shadow and small scale fading. Moreover, the impact of spatial dependence is also taken into consideration.

Recently, studying the hop count of cognitive radio ad-hoc networks (CRAHNs) has attracted increasing attention from researchers. In CRAHNs, the secondary users (SUs) coexist with the primary user (PUs). The SUs opportunistically utilize the licensed frequency bands of PUs so that the utilization of spectrum resource can be significantly improved. When PUs appear, the SUs have to evacuate the borrowed licensed bands and move to other available ones. In the worst case, some SUs may fail to detect any available channels and have to stop their communications until idle channels emerge. Consequently, the number of SUs which are able to participate in path establishment is reduced. As a result, communication paths among SUs may be longer or cannot be established. The hop count distribution of CRAHNs with shadow fading is studied in [14]. From the results obtained from the proposed simulation analysis framework, the authors show that although shadow fading helps to reduce the average path length, it significantly degrades the path connectivity.

It should be noticed that all aforementioned works assume that wireless nodes use omnidirectional antennas. There have been many research works in the literature studying the benefits of utilizing directional antennas. Specifically, the impact of randomized beamforming on the topological connectivity of multihop wireless AHNs is analyzed in [15]. Using the simulation analysis approach, the authors show that randomized beamforming scheme significantly improves the path connectivity, P_{path}, compared to networks with omnidirectional antennas with the same power and sensitivity. In [16], the effects of beamforming on the connectivity of wireless AHNs is further investigated by additionally considering two more beamforming schemes, i.e. greedy and center-directed beamforming schemes. Besides the path connectivity, the probability that a randomly chosen node does not have any connections to other nodes is also examined. The authors of [17] derive an mathematical model for evaluating the impact of shadowing and two beamforming schemes, i.e. randomized and center-directed beamforming schemes, on the probability of node isolation in wireless AHNs. With regard to the topic of beamforming in CRAHNs, the sector rendezvous problem for SUs equipped with directional antennas in cognitive radio networks (CRNs) is addressed in [18]. Then, fully distributed sector rendezvous schemes for the SU sender and SU receiver are proposed. It is proven that the proposed sector rendezvous schemes can guarantee a successful sector rendezvous within a bounded time. In [19], the authors show that the SU throughput can be improved by exploiting directional spectrum opportunities in secondary networks. They also investigate the connectivity of random CRNs with different routing schemes, namely, the horizontal data path-vertical data path (HDP-VDP) routing and circumventing routing. The authors of [20] design an energy-efficient hybrid common control channel (CCC)-based medium access control (MAC) protocol for CRNs. Subsequently, a directional antenna-based data transmission, which can reduce the node power consumption and enhance network throughput through spatial reuse, is implemented. Routing protocols for CRAHNs where SUs employs directional antennas to improve the network performance are proposed in [21,22]. The influence of beamforming on the connectivity of CRAHNs is considered in [23]. An analytical framework for evaluating the impact of shadowing and beamforming on the topological connectivity of CRAHNs is presented in [24]. The authors of [25] conduct intensive simulations to investigate the impact of beamforming on the path connectivity in CRAHNs.