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Cooperative schemes for path establishment in mobile ad-hoc networks under shadow-fading

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ABSTRACT

The performance of routing protocols for multi-hop path-establishment in Mobile Ad-hoc NETworks (MANET) is examined when the individual radio links undergo shadow fading of parameterized severity. Such propagation modeling is typical of ground-level networking along with node mobility. The metrics of main interest are the probability of having a reliable multi-hop path plus the temporal statistics of such availability under a Markovian model. Such availability is an indicator for the suitability of the network to carry delay-sensitive applications (push-to-talk voice, streaming video) in uninterrupted manner. It is shown that high levels of diversity are necessary in such adverse environments, as obtained either by multiple independent paths or via concurrent cooperative transmission. Analytical and simulation comparisons of typical routing options are presented on the above metrics, plus on the required nodal engagement for supporting such diversity.

1. Introduction

This paper deals with the issues of multi-hop MANET routing that have direct applications in either the tactical edge of military communication or in institutional environments (fire departments, emergency crews, police, etc.) [1,2]. Such networks invariably encounter challenging RF propagation environments and cannot a priori assume a fixed communication infrastructure (like a cellular system) available; therefore their operating environments and usage considerations pose unique challenges. Since nodes are both mobile and typically in rich scattering environments, link-level connectivity is unreliable and the resulting network topology is highly dynamic. Furthermore, low-latency, network-wide broadcast – as opposed to latency tolerant, randomly-paired unicast – and robust connectivity are their primary requirements. This set of challenges calls for a paradigm shift exploiting advanced concepts such as autonomous cooperative communication in order to arrive at a rapidly forming and self-controlled, robust network fabric that exploits adaptive routing and packet-switching mechanisms. The focus of this paper will be on cooperative path establishment mechanisms for MANETs that will provide the required robustness and reliability required for supporting real-time applications. The main contribution is the consideration of cooperative path establishment schemes for random MANET topologies assuming ground propagation effects, not only related to distance but also related to block shadowing effects. When shadowing varies with time it may seriously degrade the performance of state of the art schemes that are based on semi-static topologies with constant Line-of-Sight hop links. Accordingly, various relaying schemes have been examined, primary among which has been a class of selective-flooding protocols.

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The first target has been a scenario with a source broadcasting delay-sensitive information (voice, real-time video) to a set of nodes reachable by multiple hops (a "hop" signifies radio-hearing range). Proper analytical and simulation tools have been created ab initio, initially for a limited-size network (20 nodes), taking into account the randomness and varying quality of the individual radio links due to ground radio propagation. On that research platform, a variety of standard and novel routing/path-establishment protocols have been instantiated and compared regarding their path-integrity abilities. The study has been extensively parameterized with respect to hearing range and propagation characteristics, with emphasis on log-normal shadowing (as typically met in practice). The established results give credence to the conclusion that highly disruptive and very novel approaches are required in order to ensure delivery of services under reasonable quality-of-service constraints, when faced with such harsh networking environments.

The paper will demonstrate (using both analysis and simulation) that cooperative schemes may provide the necessary diversity to overcome the topology variations due to shadowing, ensuring the robustness of the MANET end-to-end connections. The paper is organized in the following way: Section 2 will present the related state of the art in the fields of path establishment and routing for MANETs. Section 3 will describe the two main categories of MANET routing schemes with respect to the level of cooperation among the transmitting nodes of each multi-hop path. Section 4 will show an analytical model for assessing the performance of both cooperative and non-cooperative schemes. Section 5 will then show comparative performance results showing the benefits of cooperative path establishment highlighting also the tradeoffs that have to be considered, in terms of the required energy and MAC/scheduling costs.

2. Related work

In general, the problem addressed by path establishment within any network consists of determining a preferable path (i.e., a sequence of intermediate network nodes) linking the source to the destination node. A simple approach, introduced in [3], was based on Autonomous Concurrent Cooperative Transmission (ACCT) which relied on flooding the network with consecutively heard-and-re-broadcast packets, which in principle would accumulate power from many received copies. However, this original concept does not involve any access coordination or timing synchronization among the neighboring nodes (or equalization processing at the nodes) which limits the effectiveness of the approach. In most cases, routing algorithms are based on graph abstractions that illustrate the network topology and the respective cost information for all possible links between the network nodes. According to the degree of network topology information available, routing algorithms may be divided into those assuming global knowledge of the network topology and link costs ("link-state" algorithms) and those assuming only local knowledge of the neighboring link costs for each node and which rely on an iterative computation process for determining path costs ("distance-vector" algorithms) [4]. Based on the routing tables, link-state algorithms (such as the Destination Sequenced Distance-Vector routing protocol (DSDV) [5] and the Optimized Link-State Routing, OLSR [6]) find for each node the optimum path based on different criteria (e.g., Open Shortest Path First OSPF, Dijkstra's Shortest Path First algorithm, etc.). On the other hand, the distance-vector-based algorithms are invoked by active nodes (reactive schemes) that try to discover a route based on the local information that they have about its neighboring nodes and on flooding the network with route request packets in order to identify a route to the respective destinations. Typical examples are the Dynamic Source Routing (DSR) [7] and the Ad hoc On-demand Distance Vector (AODV) routing protocols [8]. The philosophy in these schemes is that topology information is only transmitted by nodes on-demand. In DSR each transmitted packet includes information about the whole end-to-end multi-hop path whereas in AODV, each node 'points' only its the next-hop neighbor and routes accordingly the packets that it receives.

Further to that, a number of hybrid schemes have been proposed, combining characteristics and properties of both proactive and reactive mechanisms. The Zone Routing Protocol (ZRP) [9] considers the transmission footprint of each node and defines thus a 'zone'. Within the zone, the protocol assumes a proactive scheme for each node's neighborhood discovery, but among different node zones the path establishment is done by using reactive mechanisms.

Most cases of traditionally-approached MANET routing schemes have revealed upon application specific problems and deficiencies caused by the architecture and the protocols used, resulting in substantial under-utilization of their potential performance [10] (or even scaling "walls"). Since relaying is not a primitive operation for standard radios, current mechanims are forced to construct a chain of receive-store-process-queue-forward-contend-transmit involving several layers. In most cases each packet transmission within a hop involves all three communication layers (PHY/MAC/NET) and has to undergo the respective processing (header addition/stripping, queuing, back-off, re-transmissions, etc.). This within-node and especially the re-contention delay induces a drastic drop on performance, not only on path latency but also on effective capacity. Additionally, in most cases, each node delegates to a single neighboring node to retransmit its packet. All other neighboring nodes that receive the packet are forced to discard it, representing a considerable waste of energy by the time the packet reaches its destination, since there is no mechanism enabling the cooperation of neighboring nodes in parallel transmissions that would allow the combination of the received packet by different transmitters (and via different paths) at the destination, especially in cases of lightly loaded networks (when, in other words, many of such nodes would otherwise be idle).

In [11] the author identified the key building blocks that should exist in any new MANET architecture to elevate MANETs to a performance plane on par with wireline networks by combining several revolutionary ideas such as: (a) a relay oriented physical layer that selectively switched