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Survey on diversity-based routing in wireless mesh networks: Challenges and solutions

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ABSTRACT

Wireless multi-hop networks often experience severe performance degradations when legacy routing algorithms are employed, because they are not optimized to take advantage of the peculiarities of wireless links. Indeed, the wireless channel is intrinsically a broadcast medium, making a point-to-point link abstraction not suitable. Furthermore, channel conditions may significantly differ both in time and space, making routing over predetermined paths inadequate to adapt the forwarding process to the channel variability. Motivated by these limitations, the research community has started to explore novel routing paradigms and design principles dealing with the wireless diversity as an opportunity rather than a shortcoming. Within this large body of research, opportunistic routing and network coding are emerging as two of the most promising approaches to exploit the intrinsic characteristics of multi-hop wireless networks, such as multi-user diversity. The aim of this survey is to examine how opportunistic forwarding and network coding can achieve performance gains by performing hop-by-hop route construction and by encoding data packets at intermediate nodes. To this end, we present a taxonomy of existing solutions, and we describe their most representative features, benefits and design challenges. We also discuss open issues in this research area, with a special attention to the ones most related to wireless mesh networks.

1. Introduction

In multi-hop ad hoc networks, wireless devices cooperate in forwarding traffic between non-adjacent nodes. In this way, multi-hop network paths can be established between any pair of nodes without relying on a pre-existing network infrastructure or dedicated network devices (i.e., routers, switches, servers, etc.) [1]. This distributed networking paradigm is not a novel concept, but it has been proposed more that two decades ago for tactical and military networks. However, the recent advances in wireless technologies, as well as the advent of new mobile devices (e.g., smartphones), have promoted its utilization for a variety of innovative application domains, ranging from sensor networks to vehicular networks and mesh networks [2]. In particular, wireless mesh networks are static ad hoc networks consisting of dedicated nodes (called mesh routers) that form a multi-hop wireless backbone used to share a limited number of fixed Internet connections with a potentially large number of static or nomadic users [3].

Due to their attractive features, such as low cost and ease of deployment [4], as well as the wide range of possible application scenarios, spanning from public safety communications to community-based networks and metro scale municipal networks [5], wireless mesh networks have received increasing attention and stimulated a large body of research activities. Indeed, wireless mesh networks inherit most of the traditional challenges of ad hoc networks [6]. In particular, it is widely recognized that performance and reliability of wireless multi-hop communications significantly depend on the ability of the routing protocol to properly select network paths, given the current network conditions. A natural design approach for dealing with the complexities of the routing problem is to simply apply to the mesh domain the routing paradigms traditionally conceived for wired networks. This design choice implicitly assumes that wireless links are similar to wired links, and that they can be represented as point-to-point connections. For example, most of the routing schemes proposed for generic ad hoc networks (such as DSR [7], AODV [8] and OLSR [9]) select a shortest path between a source and destination pair, and forward each packet through a predetermined sequence of network devices, while assuming that link-layer retransmissions provide a reasonable level of communication reliability. Henceforth, we refer to this category of networking protocols as *legacy routing* solutions. However, wireless links are fundamentally different from wired links. First of all, the wireless channel is an intrinsic *broadcast medium* that has

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not clearly observable boundaries outside of which nodes are always unable to communicate. This implies that wireless links with intermediate packet loss rates, even higher that 50%, are quite common in typical outdoor mesh environments [10,11]. Furthermore, wireless medium has time-varying and asymmetric propagation properties due to a variety of phenomena, including interference from external signals, wireless propagation impairments and fading [12].

The above considerations on the peculiarities of the wireless communications suggest that, in order to improve the performance of wireless mesh networks, it is necessary to consider link qualities when choosing the best route between a source–destination pair. Indeed, a large body of research has been carried out in this area and different routing metrics have been proposed. The first metric proposed for wireless mesh networking is the ETX [13], which defines the cost of a link between a node and one of its neighbors as the expected number of transmissions that node requires to successfully deliver a packet to its neighbor. However, the implementation of this metric has shown poor performance in multi-rate environments, and an extension, called ETT [14], has been proposed, which defines the link cost as the time a data packet requires to be transmitted successfully. On the other hand, recent work has established that to correctly represent the quality of a link in a multi-hop environment, a routing metric should be able to capture other aspects of the wireless domain, such as the location-dependent nature of the link-layer contention (for instance, see CATT [15] and ETP [16] proposals), or the inter-flow and intra-flow interference (e.g., IRU [17]).

Some of the proposed link-aware routing metrics have been implemented and tested in real network deployments, and experiments have shown that they can achieve significantly higher performance compared to a classical shortest-path routing algorithm. However, all these legacy routing protocols *pre-compute* one or more minimum-cost paths (see, for instance, multi-path schemes described in [18–20]) for each source–destination pair. Experimental evidence [23,25,38] has also proved that using predetermined paths can be ineffective in dealing with unreliable and varying wireless environments. For these reasons, recently researchers have been investigating radically new routing approaches, which exploit the multiple transmission opportunities that the broadcast nature of the wireless medium creates. More precisely, whenever a packet is transmitted, it is simultaneously received by multiple nodes, which may experience significantly different channel conditions. This property is called *multi-user diversity* because it refers to a type of spatial diversity existing across multiple receivers (or users) [21,22]. This intrinsic diversity of the wireless environment is not a drawback per se, but it may cater for new design principles and alternative routing paradigms. Several protocols can be included in this novel class of routing strategies that exploit receptions of the same packet at multiple nodes to increase network performance compared to legacy routing. In this survey, we give a comprehensive review of two of the most promising design approaches: *opportunistic forwarding* and *network coding*.

Opportunistic routing algorithms implement forwarding decisions in a hop-by-hop fashion, and they defer the selection of the next hop for a packet until they have learnt the set of nodes which have actually received that packet [23]. This permits to optimize the selection of the packet forwarder(s) and to discover on the fly the best network path. This strategy clearly departs from the design principles of legacy routing, which assigns a predetermined next hop to each packet. It is also important to note that the term "opportunistic" refers to a wider class of routing algorithms based on the common idea of leveraging any transmission opportunity rather than imposing the packet transmission along a predetermined path. For instance, opportunistic routing is also used in intermittently connected networks [24]. However, in that context, communication opportunities are generated by mobility, which enables pair-wise contacts between nodes. In contrast, in this survey we limit ourselves to static networks, where transmission opportunities rely on the variability of channel conditions and the broadcast nature of the wireless medium.

The second design principle we analyze in this survey is wireless network coding, which allows the network nodes to combine/encode the data packets they receive, so as to compress data information and to increase the innovative content carried into each packet [25]. At the same time, network coding may increase reliability of packet transmissions because each encoded packet mix information about multiple packets, thus increasing the probability that they would reach their destination. It is also useful to note that the boundary between network coding and opportunistic forwarding may be blurred in some cases, when both approaches are jointly used. In these cases, we will prefer the term *hybrid* routing to point out that network coding and opportunistic forwarding are integrated into a unified routing scheme.

The above discussion provides only a brief insight into the reasons of performance gains achievable with opportunistic forwarding and network coding. The objective of this survey is to analyze in a thorough way the various conditions in which these two routing paradigms may provide the most significant performance improvements. To this end, not only we use simple illustrative network scenarios, but we also build a comprehensive classification of the main approaches that can be adopted to implement such strategies. Then, we use our classification as a roadmap to analyze the design challenges that diversity-based routing paradigms need to address, and to describe the features, advantages and disadvantages of the most representative solutions proposed in the literature. Finally, we discuss the open issues in this research area, with a special attention to the ones most related to the wireless mesh scenario.

The rest of this paper is organized as follows. Section 2 describes the three main classes of routing approaches that are the focus of this survey, and it introduces their classification. Section 3 overviews some of the most representative proposals for each class of approaches. Section 4 presents a comparison of the main features of the reviewed solutions. Finally, section 5 draws conclusions and highlights the main open issues in this research area.

2. Background and taxonomy

In this section, we overview the general routing approaches that can be adopted to take advantage of opportunistic forwarding and network coding in wireless mesh networks. Specifically, we introduce three main routing categories and several related sub-categories. Then, we describe the representative features, benefits and design challenges of these three classes of routing approaches.

2.1. Opportunistic routing

The opportunistic-based routing concept considered in this study is characterized by two main features: (i) any node overhearing a packet transmission is involved in the forwarding process, and (ii) the selection of the next forwarding node(s) is deferred after packet reception [23]. As previously explained, legacy routing algorithms rely on transmitters that select one or more designated next hops before delivering the packets, which implies that each packet must know a priori its next relay(s). However, this design principle borrowed from the routing protocols for wireline networks, does not appear suitable for wireless networks. Indeed, it masks the broadcast property of wireless communications under an artificial point-to-point link abstraction [21]. On the contrary, opportunistic routing fully embraces the broadcast nature of