Opportunistic Routing in Wireless Networks

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Foundations and Trends® in Networking

Published, sold and distributed by:
now Publishers Inc.
PO Box 1024
Hanover, MA 02339
United States
Tel. +1-781-985-4510
www.nowpublishers.com
sales@nowpublishers.com

Outside North America:
now Publishers Inc.
PO Box 179
2600 AD Delft
The Netherlands
Tel. +31-6-51115274

The preferred citation for this publication is

T. Javidi and E. Van Buhler. *Opportunistic Routing in Wireless Networks.* Foundations and Trends® in Networking, vol. 11, no. 1-2, pp. 1–137, 2016.

This Foundations and Trends® issue was typeset in LaTeX using a class file designed by Neal Parikh. Printed on acid-free paper.

ISBN: 978-1-68083-151-1

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Foundations and Trends® in Networking, 2016, Volume 11, 4 issues. ISSN paper version 1554-057X. ISSN online version 1554-0588. Also available as a combined paper and online subscription.

Foundations and Trends® in Networking
Vol. 11, No. 1-2 (2016) 1–137

DOI: 10.1561/1300000021

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Contents

Abstract

Wireless multi-hop networks have become an important part of many modern communication systems. Opportunistic routing aims to overcome the deficiencies of conventional routing on wireless multi-hop networks, by specifically utilizing wireless broadcast opportunities and receiver diversity. Opportunistic routing algorithms, which are specifically optimized to incorporate into the routing decisions a model of wireless transmission, take advantage of scheduling, multi-user, and receiver diversity gains and result in significant reduction in the expected cost of routing per packet. The ability of the algorithm to take advantage of the aspects of wireless transmission, however, depends on the scalability and the additional overhead associated with the opportunistic routing as well as the availability of side information regarding wireless channel statistics, topology, etc. This manuscript sheds light on the performance gains associated with incorporating into the routing strategy the nature of wireless transmission and devises algorithms and solutions to realize these gains in a scalable, practical, and low cost manner.

This manuscript first provides an overview of various opportunistic distance-vector algorithms that have been developed to incorporate wireless transmission and routing opportunities. Furthermore, an optimal opportunistic distance metric is proposed whose construction follows from a dynamic programming characterization of the problem. The performance of the optimal routing is then examined against the performance of several other known routing algorithms. To allow for a scalable and distributed solution, the distributed computation of this optimal distance-metric is provided. The performance of a distributed implementation of the optimal opportunistic routing algorithm is also examined via simulation.

In addition to the construction of the opportunistic schemes in centralized and distributed fashions, this manuscript also addresses how learning the wireless medium can be efficiently incorporated in the structure of routing algorithm. Finally, this manuscript examines the dynamic congestion-based distance metric and its performance against other congestion aware solutions in the literature.

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DOI: 10.1561/1300000021.

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Introduction

Wireless multi-hop networks have become an important part of many modern communication systems. Some of the earliest examples were military communication networks utilizing wireless relays in remote areas. More recently, many industries have used wireless multi-hop networks to create a multitude of fascinating tools and systems. Take, for example, the health-care industry. Body-area networks utilize many small sensors that transmit data wirelessly from node to node until it reaches a data collection node. This design allows for a robust low power network, keeping the sensors small and low cost. The same goes for environmental monitoring, such as distributed water quality sensing. The ever-growing Internet of Things (IoT) brings mesh networks into the home with products such as ZigBee and many others. As data collection and communication grows, it will be increasingly important to maximally utilize the wireless resources.

Motivated by classical routing solutions in the Internet, conventional routing attempts to find a fixed path along which the packets are forwarded [46]. Such fixed path schemes fail to take advantage of the broadcast nature and opportunities provided by the wireless medium, and result in unnecessary packet retransmissions. To the best knowledge of the authors, the first articles that noticed the benefits of opportunistic receiver selection and selection diversity were those of Lott and Teneketzis [36] and Larsson [34]. Much research interest followed and several opportunistic routing algorithms were developed [56, 12, 27]. Later, in [37], Lott and Teneketzis further developed their framework which unified many of the algorithms. In opportunistic routing, decisions are made in an online manner by choosing the next relay based on the actual transmission outcomes as well as a rank ordering of neighboring nodes. In other words, opportunistic routing mitigates the impact of poor wireless links by exploiting the broadcast nature of wireless transmissions and the path diversity.

The purpose of this manuscript is to provide the motivation for opportunistic routing, and present several different algorithms which achieve better performance, in most scenarios, than conventional shortest path routing. For select algorithms, we'll prove their properties and examine their advantages and disadvantages through theory, examples, and simulations.

1.1 Overview and Organization

We end the introduction with an overview of this study. In Chapter 2 we take a closer look at opportunism and receiver diversity in the context of wireless multi-hop networks. Examples are provided to further clarify the concepts.

In Chapter 3, we bring to our focus the problem of opportunistic routing in the multi-hop wireless network context. We start with a background on the concept of distance-vector routing, which is the basis of the algorithms studied in this manuscript. Then, using a probabilistic description of wireless links, we cast opportunistic routing as a distributed Markov decision problem (MDP) and introduce a stochastic variant of distributed dynamic programming [6] which provides a unifying framework for various versions of opportunistic routing such as Selection Diversity Forwarding (SDF) [34], Geographic Random Forwarding (GeRaF) [56], Stochastic Routing [36] and EXOR [12] where the variations are due to the authors' choices of routing cost.

In many multi-hop wireless networks, the centralized algorithm described in Chapter 3 is not practical to implement. In Chapter 4, we examine three algorithms which compute the optimal distance metric in an asynchronous distributed fashion. Theoretical foundations for the algorithms are provided.

In Chapter 5, we address the problem of opportunistically routing packets in a wireless multi-hop network when zero or erroneous knowledge of transmission success probabilities and network topology is available. Using a reinforcement learning framework, we introduce a distributed adaptive opportunistic routing algorithm (d-AdaptOR) that minimizes the expected average cost for routing a packet from a source node to a destination.

In Chapter 6, we embark upon the issue of congestion by contrasting the opportunistic MDP-based schemes with some back-pressure opportunistic schemes [42]. We propose a modification of the MDP framework to arrive at a congestion-aware policy called Opportunistic Routing with Congestion Diversity (ORCD) that exhibits significant delay improvements over existing candidates in the literature [22]. While the idea of combining back-pressure with shortest path computation is not a new one, the exact form according to which ORCD (and its variants) integrate these concepts significantly differs from the addition of the two measures proposed in [18] or constraining back-pressure routing to those nodes with a low number of hops [33]. Through extensive simulations and numerical examples, we underline the advantages of ORCD and its variants over existing solutions, while from a theoretical standpoint, we intuitively relate the structure of ORCD to that of throughput optimal routing.

In Chapter 7, we describe an 802.11 compatible implementation for the various opportunistic routing protocols discussed in this manuscript. This set of practical considerations becomes a vehicle to verify and critique the channel models associated with opportunism and receiver diversity. In particular, practical modification of the algorithms such as opportunistic routing with partial receiver diversity and equal power-rate allocation are shown to be sufficient.

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