Ad Hoc Networks 11 (2013) 2147–2171

Contents lists available at SciVerse ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

A cross-layer framework for multiobjective performance evaluation of wireless ad hoc networks

Katia Jaffrès-Runser [a,b,*], Mary R. Schurgot [a,1], Qi Wang [d,c], Cristina Comaniciu [a], Jean-Marie Gorce [c]

[a] Dept. of Electrical and Computer Engineering, Stevens Institute of Technology, Hoboken, NJ 07030, USA
[b] Université de Toulouse, INPT-ENSEEIHT/IRIT, Toulouse, France
[c] Université de Lyon, INRIA/INSA-Lyon, CITI, Lyon, France
[d] Institute of Computing Technology, Chinese Academy of Sciences, Beijing, China

ARTICLE INFO

Article history:
Received 5 November 2012
Received in revised form 15 February 2013
Accepted 4 April 2013
Available online 29 April 2013

Keywords:
Multiobjective optimization
Cross-layer design
Ad hoc networks
Performance evaluation

ABSTRACT

In this paper we address the problem of finding the optimal performance region of a wireless ad hoc network when multiple performance metrics are considered. Our contribution is to propose a novel cross-layer framework for deriving the Pareto optimal performance bounds for the network. These Pareto bounds provide key information for understanding the network behavior and the performance trade-offs when multiple criteria are relevant. Our approach is to take a holistic view of the network that captures the cross-interactions among interference management techniques implemented at various layers of the protocol stack (e.g. routing and resource allocation) and determines the objective functions for the multiple criteria to be optimized. The resulting complex multiobjective optimization problem is then solved by multiobjective search techniques. The Pareto optimal sets for an example sensor network are presented and analyzed when delay, reliability and energy objectives are considered.

1. Introduction

Wireless ad hoc and sensor networks often operate in difficult environments and require several performance criteria to be satisfied related to the timely, reliable, and secure exchange of data. To enable communication across the network, key design elements include routing and resource allocation protocols. Various constraints related to transmission delay [1], energy consumption [2] or fairness [3,4] are added to the protocol's main design goal of reliable information transfer. Thus, the assessment of such protocol performance relies on various criteria measures which may be evaluated analytically or through network simulations.

It is possible to understand the capabilities and limits of a routing protocol or a resource allocation strategy if a bound on the network performance is known. An end user requires certain simultaneous levels of performance for multiple criteria to guarantee quality of service, yet the considered performance metrics often conflict. The solution maximizing for instance capacity may not be the one that minimizes delay. Therefore all of these performance metrics have to be considered concurrently in the optimization process. In the case of multiple criteria, however, there is usually no single optimum and several solutions offering different optimal trade-offs exist. More specifically, if you decide to optimize delay and capacity, you will

* Corresponding author. Address: Université de Toulouse, INPT-ENSEEIHT/IRIT, 2 rue Charles Camichel, BP 7122, 31061 Toulouse Cedex 7, France. Tel.: +33 5 34 32 21 90.

E-mail addresses: katia.jaffres-runser@irit.fr (K. Jaffrès-Runser), maschurg@lgsinnovations.com (M.R. Schurgot), wangqi08@ict.ac.cn (Q. Wang), ccomanic@stevens.edu (C. Comaniciu), jean-marie.gorce@insa-lyon.fr (J.-M. Gorce).

[1] Mary R. Schurgot is now with LGS Bell Labs Innovations. This work was completed while a Ph.D. candidate in the Dept. of Electrical and Computer Engineering at Stevens Institute of Technology.

1570-8705/$ - see front matter
http://dx.doi.org/10.1016/j.adhoc.2013.04.006

find solutions (*i.e.* routing and resource allocation strategies) in the Pareto optimal set that favor either capacity, delay, or some trade-off combination. The main contribution of this paper is to propose a unified cross-layer framework capable of capturing the trade-offs existing between multiple performance metrics.

The solution we propose for obtaining bounds on multiple benchmark objectives relies on the definition of a multiobjective optimization problem; the subsequent evaluation provides a set of Pareto optimal solutions. The Pareto set is composed of non-dominated solutions, i.e. solutions of the search space that are never dominated by any other with respect to the evaluation criteria considered. A solution herein characterizes one possible route configuration with its resource allocation defined in terms of transmission rate. For example, a possible solution to facilitate the transfer of information from source to destination could be the selection of an intermediate node to relay the data with a fixed transmission rate. This multiobjective optimization problem is hard to solve since it is the combination of a resource allocation problem and a routing problem. Compared to analytical approaches, it has the drawback of being computationally more expensive but has two main advantages. First, it can be used to derive bounds for multiple performance metrics at a time. Second, it not only provides the performance bounds, but also extracts the solutions that are Pareto optimal which cannot be determined using a classic analytical approach.

In order to mitigate the limitations of the layered network architecture, cross-layer interactions have to be considered in the framework definition. In [5], the authors address a cross-layer optimization problem of joint design of routing, Medium Access Control (MAC), and physical layer protocols with cooperative communication to achieve minimum power cost under a specified per-hop packet error rate (PER) objective in wireless sensor networks. The authors in [6] highlight the need to find "a simple interface to the physical layer that allows the upper layers to achieve optimal or near optimal cross-layer performance based on the underlying channel conditions". For the cross-layer model we describe in the following sections, we define a link probability–the probability a packet arrives over a given link. This parameter serves as an *interface* between network layer routing/link layer management decisions and expected physical layer performance by leveraging the broadcast nature of wireless transmissions. The variables of our multi-objective optimization problem determine how often and when a node should re-broadcast a received packet. The approach we take in this work provides for the characterization of fundamental upper bounds, the tradeoff space of multiple criteria, and the routing and resource allocation decisions to achieve these tradeoffs. This approach mirrors the key research areas proposed in the framework of [6]. The authors describe the need for joint research in the areas of fundamental performance upper bounds, layerless dynamic network performance, and application and network optimization. It is through the interaction of these research areas that ad hoc network design and performance can be related and formalized.

Understanding the trade-offs involved with various routing solutions will enable adaptive resource management across layers and nodes, leading to a more accurate "local to global performance mapping" for practical routing protocol design. The identification of Pareto optimal solutions provides not only achievable performance bounds, but also specific solution sets for the routing and resource allocation algorithms to operate at those bounds. In this paper, we propose a novel framework capable of providing a bound for joint optimization of multiple performance metrics. Our proposed framework comprises both a probabilistic cross-layer network model and a multiobjective optimization problem formulation. Our proposed cross-layer network model captures more accurately the interactions between routing decisions and resource allocation, assuming a basic random medium access control protocol. With its intrinsic probabilistic definition, it is capable of defining various routing techniques such as multi-hop single path routes, broadcast protocols or multi-path protocols. The multiobjective optimization problem is solved using the Parallel Multiobjective Tabu Search (PMOTS) algorithm to retrieve the set of Pareto optimal solutions. This global cross-layer multiobjective framework is applied herein to tackle the problem of robust routing and resource allocation for wireless sensor networks. The following three criteria are relevant in this context: (i) reliability defined as the probability of having a successful packet transmission, (ii) delay, defined as the average end-to-end delay in the network, and (iii) the forwarding energy, defined as the energy spent by the network for relaying.

The goal of our work is different from other approaches aimed to *distributively* compute Pareto optimal routing algorithms with respect to multiple performance criteria as proposed in [7,8]. Our aim is not to develop a new routing algorithm, but to provide a general framework capable of capturing the performance trade-offs of a given network by computing the set of Pareto optimal routing strategies. This characterization provides an efficient tool to:

- compare the performance of existing routing algorithms to the bound provided by the set of Pareto optimal strategies, and
- foster the development of more efficient and flexible routing strategies based on end-user requirements for network performance.

Our main contributions in this work are twofold:

1. Propose a general cross-layer framework network model capable of capturing the impact and interaction of a wide range of interference and resource management techniques for various channel conditions.
2. Formulate a multiobjective routing optimization problem by defining appropriate evaluation functions for criteria such as reliability of information transfer, end-to-end delay, and energy consumption.

The multiobjective routing optimization problem described in the following can be solved using existing multiobjective search techniques [9]. Our paper focuses mostly on the derivation of the proposed cross-layer framework, and gives only a brief description of the optimization