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Traffic Engineering for wireless connectionless access networks supporting QoS-demanding media applications

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ABSTRACT

This paper focuses on the problem of optimal QoS Traffic Engineering (TE) in Co-Channel Interference (CCI)-affected power-limited wireless access networks that support connectionless services. By exploiting the analytical tool offered by nonlinear optimization and following the emerging "Decomposition as Optimization" paradigm [1], the approach pursued in this paper allows to develop a resource allocation algorithm that is distributed, asynchronous, scalable and self-adaptive. Interestingly, the proposed algorithm enables each node of the network to distribute its outgoing traffic among all feasible next-hops in an optimal way, as measured by an assigned global cost function of general form. This optimal traffic distribution complies with several subjective as well as objective QoS requirements advanced by the supported media flows and involves only minimum information exchange between neighboring nodes. Furthermore, it allows for load-balanced multiple forwarding paths and it is able to self-perform optimal traffic re-distribution (i.e., re-routing) in the case of failure of the underlying wireless links. Finally, actual effectiveness of the overall proposed algorithm is numerically tested via performance comparisons against both DSDV-based single-path routing algorithms and interference-aware multipath routing algorithms.

1. Introduction and motivation

Emerging high quality real-time wireless media applications, such as Voice over Wireless IP (VoWIP) and wireless video phone, present strict delay, delay-jitter as well as power-saving requirements, which cannot be adequately supported by the current wired-oriented Internet Protocols [2,3]. As a result, recently, a number of new Internet-friendly protocols has been developed in the attempt to meet this demand. Specifically, Multiprotocol Label Switching (MPLS) has been envisioned as a reliable 2.5-layer platform upon which QoS services could be developed [4]. MPLS achieves service guarantees by setting up and managing a set of primary and secondary labels switched paths over the underlying IP domain. Being the MPLS architecture inherently connection-oriented, it also requires the implementation of a suite of additional protocols to perform link-failure recovering. This implies that, providing real-time wireless applications requires a *substantial* modification of the IP core routers and brings about the need of addressing the scalability and the complexity entailed by the existing solutions when applied at global scale.

Therefore, a key question still to be tackled concerns actual possibility to enable QoS-services in the power-limited CCI-affected wireless domain by relying *only* on the functionalities offered by the current connectionless IP architecture. In this paper, we present and test an optimization-based framework which makes it feasible. In particular, we develop a flexible, distributed and self-adaptive TE-based resource allocation algorithm that involves all layers of the Internet protocol stack and allows optimal multipath QoS routing, flow control and load-balancing. The pre-

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sented algorithm drives the network to an operation point where a suitably defined *global* cost function is minimized. Furthermore, it allows fast time-scale TE via multipath load-balancing and adaptive link-based power-control, that, in turn, guarantee automatical optimal repartition of the network flows over the still feasible source–destination paths when link failures occur. Doing so, the resource allocation algorithm retains, by design, the capability to enable *optimal scalable QoS-TE and failure-recovery*, simultaneously. Furthermore, since the optimization framework allows point-to-point multipath in a distributed and asynchronous way, the resulting resource allocation algorithm may be *directly* implemented in IP-based wireless networks, so as to guarantee the QoS demands advanced by real-time media applications.

1.1. Related work

Application of TE principles to *wired* networks supporting connectionless services is still under investigation [4–10]. Specifically, [5] shows that, by properly assigning link-weights based on a given traffic demand matrix, the uneven traffic distribution among equal-cost multiple shortest paths may lead to a globally optimal TE solution which, in turn, is implementable upon Open Shortest-Path First (OSPF) networking architectures. After recognizing that the solution proposed in [5] is centralized, [6] develops a family of distributed control laws that operates at the Network layer and proposes a load-balanced failure-resistant multipath routing algorithm. This approach was successfully extended in [7] for simultaneously achieving cross-layer distributed flow-control at the Transport layer and load-balanced multipath routing at the network one. Following the same research trend, decentralized gradient-based algorithms have been developed in [4,8] that aim to support point-to-point load-balanced multipath routing of multiple elastic traffic flows. In order to solve the same problem in congestion-affected instability-prone scenarios, novel multi-layer approaches based on the maximization of suitable global utility functions have been proposed and tested in [9,10]. Although these contributions represent an important step towards the application of TE to the support of connectionless services, they all focus on *wired*, and therefore CCI-free, networks.

How to actually apply TE principles to design networks guaranteeing QoS and providing connectionless services in the wireless (possibly, mobile) domain is still an open question. Up to date, most published works addressing resource allocation in wireless networks neglect the connectionless/connection-oriented nature of services and directly exploit the analytical tools for nonlinear optimization to solve *multi-layer* resource optimization problems. In this context, a first group of works aims at reducing the problem complexity by assuming orthogonal access. When transmit nodes are allowed to use nonoverlapping channels (as in the Time or Frequency Division Multiple Access networks in [11,12]), or primary conflict-free schedulers are implemented (e.g., by means of graph coloring [13]), or link capacities and/or flow rates are directly assumed to belong to *convex* resource sets [14,15], the routing problem becomes an instance of convex optimization. The same conclusion holds when hidden convexity properties of the capacity function may be exploited via suitable algebraic transformations of the involved variables [16,17].

When the underlying system constraints do not allow completely orthogonal access policies and nonnegligible CCI-effects arise, the optimization problem to be tackled becomes nonconvex. In this case, proposals in Literature either embed in their framework scheduling policies or develop manageable (convex) approximation of the original problem. As to the former, the proposed solutions (as the one in [18]) entail high complexity implementation since conflict-free scheduling was proved to be NP-hard in [19], even for TDMA-based centralized policies. As to the latter, in [20,21], a QoS power-allocation problem for CDMA-based systems is proved to be convex if, and only if, the Signal to Interference plus Noise Ratio (SINR) can be expressed as a log-convex function of the QoS parameters. Similarly, in [22], the authors derive two conditions on the capacity function that convexify the tackled joint power-control, multipath-routing and congestion-control problem. Although directly solvable by common numerical optimization tools, such approaches suffer from the fact that low SINRs may give rise to *negative* link-capacity values. This provides a strong motivation to investigate the following: is it possible to compute the *exact* (i.e., *nonapproximate*) solution of a CCI-affected nonconvex power allocation problem by means of a suitably designed *convex* problem? Main result of this contribution is that, under the conditions detailed in Section 4, we can, indeed, answer in the affirmative.

The remainder of this paper is organized as follows. In Section 2, we describe the considered network model. In Section 3, we give the analytical formulation of the POP along with a description of its constraints. Section 4 presents the proposed two-level decomposition solution and its structural properties. The development of power-allocation and MAC-design distributed algorithms is the focus of Section 5, whereas numerical results, performance comparison and conclusive remarks are presented in Sections 6 and 7, respectively. Proof of the main analytical results are provided in the final Appendix.

About the adopted notation, $\mathbf{A} \equiv [a(v,l),\ v = 1,\ldots,V;\ l = 1,\ldots,L]$ indicates a $(V \times L)$ matrix with (v,l)th entry equal to $a(v,l)$, whereas $\vec{b} \equiv [b_1,\ldots,b_L]^T$ represents an $(L \times 1)$ column vector. Furthermore, $\vec{e_i} \in \mathbb{R}^V$ is the ith unit vector of $\mathbb{R}^V$, while $\vec{O}_L$ and $\vec{1}_L$ are the $(L \times 1)$ vectors with all zero and all unit entries, respectively. Finally, $\log(\cdot)$ is the natural logarithm and $f^{-1}(y)$ is the inverse of the scalar function $y = f(x)$.

2. Network model

We represent the considered wireless network as a directed graph $\mathcal{G} \equiv (\mathcal{V}, \mathcal{L})$, where $\mathcal{V}$ (with cardinality V) is the set of nodes and $\mathcal{L}$ (with cardinality L) is the set of feasible links. Formally, a directed link l from the transmit node $t(l)$ to the receive one $r(l)$ is feasible when the gain $g(t(l),\ r(l))$ of the corresponding physical channel: $t(l) \to r(l)$ is *strictly* positive. In practice, link l is feasible when the receive node $r(l)$ falls within the transmission