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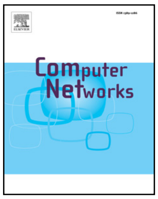

A multi-timescale cross-layer approach for wireless ad hoc networks

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ABSTRACT

Conventionally, cross-layer designs with same timescale updates can work well; however, there is a difference in layers' timescales and each layer normally operates at its corresponding timescale when implemented in real systems. To respect this issue, in this article, we introduce a multi-timescale cross-layer design along with three sets of constraints: congestion control, link delay, and power control and with the objective of maximizing the overall utility and minimizing the total link delay and power consumption. The proposed procedure can be implemented in a distributed fashion, which not only guarantees truly optimal solutions to the underlying problem, but also adheres to the natural timescale difference among layers. Finally, the numerical results further solidify the efficacies of our proposal compared to the current frameworks.

1. Introduction

Flow control in wired networks was firstly modeled as a network utility maximization (NUM) paradigm [1,2], as follows:

$$\max_{x\geq 0} \sum_{s} U_s(x_s) \qquad (1)$$
$$\text{s.t.} \quad Rx \leq c,$$

where x is the source rate vector, R is the routing matrix, and c is the fixed link capacity vector. In wireless networks, however, the link capacities c might be changed due to characteristics of wireless channel [3,4]. Accordingly the problem (1) should be solved using Cross-Layer Designs (CLDs) by decomposing into subproblems, each of which corresponds to a layer. In fact, CLDs are essentially needed for wireless networks since CLDs can improve the network performance and reliability, for example, increasing throughput and reducing latency and bit error rate [5].

There exist lots of works mainly focusing on CLDs for wireless networks [3,5–11]. In [8], they not only considered a congestion control problem but also examined the effects of the lossy feature on the power control and link delay, namely Rate-Effective NUM (RENUM), with constraints on rate outage probability, data rate reduction, and delay-constrained traffics by taking them into consideration of the objective function. The rate outage probability is, however, based on the approximated form; therefore, RENUM may just produce suboptimal solutions to the problem [9]. In [12], we studied a cross-layer design which can guarantee the globally optimal solutions to the RENUM. However, a common limitation of these works is that optimization variables at different layers are all updated simultaneously.

Each one of the five-layers in the TCP/IP network model takes its own networking functionalities and adheres to the distinct timescale. For an extreme example, the PHYsical layer (PHY) roles are to perform functions of power

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control and rate adaptation, while admission control, multi-flow control, and congestion control are performed at the transport layer. Practically, the TRANsport (TRAN) layer is executed on the second timescale, while the data link control/MAC (DLC/MAC) layer and the PHY layer are executed on the scale of, respectively, milliseconds and microseconds. The precise timescales offer significant benefits of convergence speed and network performance [11]. Multi-timescale CLDs can be found in [11,13–21]. The authors in [11,16] developed joint CLDs of congestion control and power allocation, which adheres to the natural timescale separation between rapid power control updates and slower end-to-end rate adjustments. In [13], the authors reported that using the standard subgradient method in tackling the joint problem of MAC scheduling and congestion control might be not suitable for some circumstances [19–21], for example, if the utility function is not concave at all primal variables such as time-share proportions of the allowed schedules in the case [13], the primal variables may be oscillated, which can be avoided by proposing a two-timescale adaptive method. Nevertheless, no mentioned literature [11,13–21] has concurrently addressed the following issues (1) fast-fading, (2) lossy features of wireless networks, and (3) link delay requirement.

In this paper, we study the problem of rate control, link delay, and power allocation for Wireless Ad Hoc NETworks (WANETs). Our objective is to find a cross-layer design that maximizes the overall utility and minimizes the total link delay and power consumption subject to constraints on outage probability, delay requirement and flow rate conservation, which not only guarantees globally optimal solutions to the underlying problem, but also adheres to the difference in layers' timescales. In a nutshell, the summary of features and contributions offered by our proposal are listed, as follows:

- In Section 3, we present the network model and then formulate a joint optimization problem. Since the original optimization problem is non-convex, we first cast the underlying one into a convex one by auxiliary variables and log-transformations and then prove the convexity and strong duality properties of the transformed problem.
- We explore our proposed procedure, namely, Multi-TimeScale RENUM (MTSRENUM) in Section 4 and make use of the primal vertical decomposition in order to derive three timescale-based subproblems: the Short-TimeScale (STS) subproblem (power control), the Mid-TimeScale (MTS) subproblem (link delay control), and the Long-TimeScale (LTS) subproblem (congestion control). Because the convexity and strong duality hold for the new optimization subproblems, each subproblem can be successively and optimally solved by the conventional duality technique and updated at its adhered timescale.
- The convergence of the proposed algorithm MTSRENUM is guaranteed, which is proven in Section 4.4.
- Simulation results in Section 5 confirm that our cross-layer design can provide large gains over the current frameworks. More specifically, by comparing the multi-timescale CLDs with their same-timescale counterparts, CLDs with multi-timescale controls illustrate the improvement in the convergence speed. In addition, it is observed that the MTSRENUM algorithm is better than the others in terms of suffered delay, consumed power, transmission rate as well as the trade-off between the aggregated effective rate and suffered delay and consumed power.

In the next section, we provide an overview of the state of the art related to CLDs and multi-timescale controls.

2. Related work

Lots of literature whose principle focus on designing optimal CLD policies have been proposed [1–3,5–12,22–25], ranging from wired networks to wireless networks. The seminal researches on network resource allocation in wireline networks have been extensively investigated in [1,2]. A survey on and challenges of CLDs in wireless networks can be found in [5,26]. In [5], the authors elaborated that CLDs can be categorized as non-manager and manager methods according to how to share information in one node and as centralized and distributed algorithms based on how to share cross-layer information among all nodes in a network. On another perspective, by the update timescale of the network, cross-layer designs can be classified into two groups: multi-timescale-based method and same-timescale-based method.

Most of popular works are the same-timescale methods. In [3], the author presented a distributed power algorithm coupling with the existing congestion control protocols in order to increase end-to-end throughput and energy efficiency of the network. In this work, the high signal-to-interference-ratio (SIR) approximation, i.e., SIR is assumed to be much higher than 1, is considered in order to cast the underlying non-convex problem into a convex one; however, this assumption just suits to the scenario where the wireless channels change very slowly while it may cause serious performance degradation in fast-fading wireless channels. Similar to [3], Papandriopoulos et al. [6] developed a distributed cross-layer design without any approximation that can attain the globally optimal solutions of link transmit powers and source rates for a mobile ad hoc network. A framework of congestion control and power allocation with an outage probability in fast-faded wireless channels has been studied in [9]. In [7], the authors firstly investigated the “leaky-pipe” flow model, called ENUM, where the transmission rate of a flow decreases along its route. Followed from [7], Guo et al. [8] proposed the RENUM framework, where the transmit power and link delay are also the optimization variables. In [10], the authors considered the problem of congestion control in interference-limited wireless networks with power control, namely ENUM with Power control (ENUMP). However, all of these works are assumed to execute at the same timescale, that of course leads to serious challenges.

Some recent works are devoted to the multi-timescale controls [11,13–21]. In [11], the authors considered a cross-layer design for congestion control and power control, respecting two timescales of the TRAN layer and PHY layer. In [15], the authors proposed a novel scheme, namely Multi-Period NUM/Adaptive Modulation (MPNUM/AP), which deals with optimal control policies at the PHY layer and upper layers at different timescales and can be solved by exploiting the Markov decision process. Literature [18] investigated a joint problem of rate adaption, power control and spectrum allocation in OFDMA-based multi-hop cognitive radio networks.