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Dynamic dual-reinforcement-learning routing strategies for quality of experience-aware wireless mesh networking

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ABSTRACT

The impact of transmission impairments such as loss and latency on user perceived quality (QoE) depends on the service type. In a real network, multiple service types such as audio, video, and data coexist. This makes resource management inherently complex and difficult to orchestrate. In this paper, we propose an autonomous Quality of Experience management approach for multiservice wireless mesh networks, where individual mesh nodes apply reinforcement learning methods to dynamically adjust their routing strategies in order to maximize the user perceived QoE for each flow. Within the forwarding nodes, we develop a novel packet dropping strategy that takes into account the impact on QoE. Finally, a novel source rate adaptation mechanism is designed that takes into account the expected QoE in order to match the sending rate with the available network capacity. An evaluation of our mechanisms using simulations demonstrates that our approach is superior to the standard approaches, AODV and OLSR, and effectively balances the user perceived QoE between the service flows.

1. Introduction

The proliferated consumption of rich media content, the common usage of personalized services and the increased trend to request any multimedia content at any time and at any device have led to a strong growth in network traffic. As reported in [1], the traffic generated by video-based services already exceeds 50% of mobile networks' traffic. Therefore, future communication networks must provide effective support for the increasing demand of multimedia traffic and, within this context, it becomes important to ensure that network resources are efficiently shared among these services in order to maximize the users' perceived Quality of Experience (QoE) [2]. While Quality of Service (QoS) is only focused on packet-based resource management and delivery statistics, QoE refers to the subjective user perception, dependent on the service received, which may allow the network to differentiate the provisioning of multiple services according to their requirements.

The heterogeneity of wireless technologies has to be considered as a key pilar of future networks. It enables the seamless support of a multitude of users characterized by different mobility patterns, price preferences, device capabilities and service characteristics. Within the scope of wireless networking, Wireless Mesh Networks (WMNs) [3] are easily deployable, comparing to the traditional wired networks that require much more deployment effort, providing broadband wireless internet access in wider areas. WMNs are characterized by high flexibility of their multi-hop and

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multi-path topologies, as the WMN nodes are endowed with self-organization and self-configuration capabilities to quickly and autonomously adapt to environmental changes.

Despite the potential of WMNs to support high speed last mile connectivity and ubiquitous broadband access, the dynamic and simultaneous provision of a variety of services over WMNs is not a straight-forward task. The wireless environment is extremely unpredictable, since transmission performance is deeply influenced by interference and collisions whenever several mobile terminals access the shared medium. Due to this reason, a variety of wireless mesh networking functions and/or protocols has to be improved to enhance the WMN multi-service support. From this perspective, different research areas and perspectives have been addressed in the literature in order to evolve WMNs by considering QoE feedbacks of mesh clients, leading to a fair distribution of WMN resources among services, and increasing the overall QoE perceived by mesh clients. At the packet level, authors have developed enhancements on QoE-aware routing [4] and packet scheduling [5], while, at the application level, QoE-aware rate adaptation schemes have been proposed [6].

Traditional WMN routing protocols are either proactive (such as OLSR [7]) or reactive (such as AODV [8]) way. However, a route, once found, will still be used even in the case of excessive packet dropping or delay due to congestion. This would result in low user perceived quality. In contrast, the work in [4] proposes a routing strategy that dynamically selects routes providing certain QoE bounds. In such an approach, reinforcement learning [9] is used to enable a WMN node to autonomously learn the best route to reach a service flow's destination by applying a trial-and-error mechanism and getting feedback from the environment, thus maximizing the overall QoE of multiple competing flows. Concerning the typical packet scheduling techniques, they are focused on the throughput and delay that can be guaranteed to a certain flow, thus not considering how the network constrained resources influence the QoE perceived by the users requesting such flows. The work presented in [5] adds QoE requirements when designing a packet scheduler for each WMN node. The scheduler first determines the impact of packet dropping on different service flows traversing such node. Then, it then applies an optimization algorithm to find the packet drop combination that maximizes the overall QoE of such flows. In addition, multi-service WMN support is not only impaired by network factors, but also by application-level ones, such as codec, bitrate or recovery mechanism. While application-level QoE-aware source rate adaptation techniques have been extensively investigated [6,10,11], they have not been applied to WMNs, since they lack the mechanisms for acquisition and dissemination of QoE feedback information back to the flow's source node, in a multi-hop fashion.

In this article, we propose a comprehensive framework for WMNs that addresses both network-based and application-based factors combining reinforcement learning and QoE-awareness, while increasing the overall user perceived QoE. We extend the work on QoE-aware routing [4] to build an overall QoE-aware wireless mesh framework, taking advantage of light-weight QoE-aware feedback signals conveyed in the headers of the data or control packets that flow the WMN. These signals are then used to predict the path quality towards the destination, *Forward Learning*, and towards the traffic source, *Backward Learning*. Both mechanisms enable a double reinforcement learning strategy for which QoE-aware knowledge is employed to preferably forward service flows through the WMN paths that lead to a better QoE. Moreover, we use the disseminated QoE knowledge to trigger adaptation rates of a video service flow at its source, reducing it down whenever the QoE feedback is bad, and increasing it after a minimum number of good QoE feedbacks. Finally, we propose a packet scheduler driven by the QoE-aware information gathered and disseminated through the reinforcement learning strategy.

By performing detailed experiments using the NS-2 simulator, we show that our QoE-aware reinforcement learning strategy together with the proposed routing and scheduling strategies significantly increase the overall user perceived QoE, when compared to the standard ad-hoc routing protocols: the on-demand AODV protocol (RFC [3561] [8]) and the link state driven OLSR protocol (RFC [3626] [7]). Moreover, with the introduction of the QoE-aware source rate adaptation algorithm, we are able to minimize the impairments in the QoE of the different services in a variety of WMN scenarios.

Compared to our previous works in [4] and [5], this article proposes a complete QoE-aware optimization approach and a thorough evaluation, with the following innovative elements:

- Overall architecture for QoE optimization in WMNs, which integrates both optimal QoE-learning and packet scheduling, and source rate adaptation, in an integrated framework.
- Packet scheduler driven by the QoE-aware information gathered and disseminated through the reinforcement learning strategy.
- Source rate adaptation driven by the QoE knowledge of a video service flow.
- Overall and thorough evaluation of the framework and the proposed approaches, considering the comparison to current approaches in the literature.

The remainder of the article is organized as follows. We review related work in Section 2. Section 3 introduces the importance of using objective QoE-aware metrics for more intelligent network control and management, and provides details on the QoE models we employ. Section 4 describes the proposed QoE-aware reinforcement learning framework for WMNs, which includes three main blocks: routing, differentiated packet scheduler, and source rate control algorithm. In Section 5, we present a performance analysis of our framework. Finally, Section 6 concludes the paper.

2. Related work

QoS metrics, such as delay, packet loss, and jitter do not represent well the user service perception of the service quality. That is because different services (such as, VoIP, IPTV, file transfer) that experience the same latency or packet loss are perceived differently by the user. Thus, recent research trends are increasingly focused on new techniques capable of maximizing the users' perceived QoE. In [12], an autonomic architecture is proposed to manage the QoE on