Joint Quality Enhancement and Power Control for Wireless Visual Sensor Networks based on the Nash Bargaining Solution

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ABSTRACT

We propose a cooperative method for resource allocation with power control in a multihop Direct Sequence Code Division Multiple Access *Wireless Visual Sensor Network* (WVSN). Typical multihop WVSNs consist of visual sensors that record different scenes and relay nodes that retransmit video data until the base station is reached. The error prone wireless environment contributes to the end-to-end video quality degradation. Moreover, the limited battery life span of the network nodes poses challenges on the management of power consumption. The different resource requirements of the WVSN nodes necessitate a quality-driven and power-aware resource allocation mechanism. We formulate the joint Quality Enhancement and Power Control problem based on a utility function that reflects both the benefit in terms of video quality and the cost in terms of transmission power. This function is employed by the Nash Bargaining Solution, which achieves higher fairness in terms of end-to-end video quality among all nodes. For the fairness assessment, a new metric is introduced. The experiments demonstrate the effectiveness of the proposed approach and explain the video quality-power consumption tradeoff as well as the resulting fairness-power consumption tradeoff.

1. Introduction

Recent advances in video coding technologies and wireless communications have provided several applications and systems, such as healthcare, public safety systems, environmental monitoring and traffic analysis [1]. A simple traditional *Wireless Visual Sensor Network* (WVSN) is usually organized in a centralized manner and consists of: a) battery-constrained visual sensors with wireless communication capability, and b) a *Base Station* (BS) that collects the information from the sensors and decides on the resource allocation among all network nodes. Since the transmission range of a visual sensor node is limited, the recorded video sequences may need to be transmitted using fixed relay nodes until they reach the BS via multiple hops. The relay nodes utilize a *decode-and-forward* protocol. In this context, each WVSN node transmission causes interference to other transmitting nodes, which lie within its transmission range, leading to the degradation of the received video quality at the BS.

Taking into account the fact that the nodes have different resource requirements and that it is crucial to optimize communication in order to minimize energy consumption and simultaneously maintain an acceptable quality of the application requirements [2], the establishment of an efficient cross-layer method that considers all these aspects is a challenging task. Most of the works in the recent literature consider the optimization of one of the aforementioned aspects (e.g. power consumption).

Despite the QoS provisioning, a power management policy is required so that the lifetime of each battery-powered node is prolonged. At the same time, the interference among nodes that transmit simultaneously causes quality degradation, which should not be neglected by the power allocation method. Particularly, a source node's video may suffer from interference caused by other source nodes in its cluster. Furthermore, in a multihop WVSN, the relay nodes can interfere with other source and/or relay nodes. As a result, the video sequence experiences successive degradation across the multihop path to the BS. Therefore, in order to avoid such degradation, it is required to control not only the source and channel coding rates and the used transmission power of the source nodes, but also the channel coding rates and the transmission power of the relay nodes. This control is performed at the BS,

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which collects all information from both source and relay nodes and manages the resource allocation. Nevertheless, the need to optimize both the end-to-end video quality and the power consumption has motivated us to propose a game-theoretic bi-objective approach that provides joint *Quality Enhancement and Power Control* (QEPC) for multihop WVSNs.

In the present work, we study the resource allocation problem in cooperative multihop *Direct Sequence Code Division Multiple Access* (DS-CDMA) WVSNs. Without cooperation, the nodes would simply act selfishly and greedily, thus would use the highest available transmission power in order to achieve the highest possible video quality at the BS. However, this would result both in excessive power consumption and intra-cell interference, consequently leading to quality degradation and higher transmission power consumption. We consider that some of the recorded scenes are correlated in terms of their position and the levels of motion. Hence, the correlated groups of visual sensors have similar resource requirements, which allows us to accordingly cluster the visual sensors and, thus, reduce the computational complexity of the resource allocation optimization problem. Furthermore, the network resources (transmission power, source and channel coding rates) have to be optimally allocated to the source and relay nodes using a quality-aware strategy, so as to maintain the end-to-end distortion at a low level for all source nodes. Moreover, power consumption control is dictated for all WVSN nodes due to limited resources [2,3].

Briefly, our aim is to define an effective approach for the bi-objective problem of jointly enhancing the end-to-end video quality and the total power consumption in WVSNs. To this end, in the present work, we assume that our WVSN nodes form coalitions and cooperate to establish a mutually acceptable resource allocation. We aim to satisfy both the objectives of enhanced end-to-end video quality and reduced power consumption by formulating a bi-objective utility function that acts as a pricing scheme by including both a benefit term and a cost term.

1.1. Related work

The problem of the resource allocation in multiple network nodes for effective video streaming has been examined in many studies [4–11] and various cross-layer techniques have been proposed. Some of them [4–8] focus on the resource allocation (e.g. bit rate or joint source and channel coding rate) for the optimization of a single objective, such as throughput maximization. Other works do not take into account the resulting power consumption, like the rate-distortion scheme in [12] which adapts the transmission policy and encoding rate to channel capacity and varying correlation level of multiple scenes. Despite their effectiveness, these single objective methods do not address the crucial issue of QEPC.

On the other hand, other studies in the recent literature [9–11, 13,14] aim to allocate the network resources by utilizing bi-objective approaches. In [9], the joint power control and scheduling problem in wireless multihop networks is formulated as a total transmission power minimization problem, while QoS for individual sessions, in terms of payload rate and bit error rate, is guaranteed. Resource allocation schemes that enable relay node selection of each user in a cooperative network and formulate a bi-objective problem, aiming at the optimization of power consumption and throughput experienced by each node are proposed in [10]. Recognizing the fact that power control itself cannot meet the QoS requirements, a joint channel and power allocation scheme for cognitive radio networks is proposed in [11]. That scheme is designed to maximize the overall throughput, while guaranteeing the proportional fairness and power distribution among the cognitive radio users.

A joint bi-objective optimization problem was formulated in [13] for a *Orthogonal Frequency Division Multiple Access* (OFDMA) system with the decode-and-forward relaying strategy. The formulated problem was transformed in a two-stage problem in order to be solved. A similar bi-objective problem was proposed in [14] in order to solve the admission control and fair resource allocation problem in a wireless multi-user (of constant and variable bit rate) amplify-and-forward relay network. Due to its combinatorial hardness, the authors proposed its transformation into an equivalent one-stage optimization problem, which can be solved with a lower computational complexity.

It is important to note that most of the proposed bi-objective problem formulations target at network-related QoS metrics optimization and not at end-to-end quality of the delivered information. Furthermore, most of these problem formulations were solved by adopting problem decomposition techniques. Instead of explicitly optimizing network-related parameters, such as bit error rate or throughput, we propose a quality-driven optimization scheme, which aims at maximizing the delivered video quality in terms of the *Peak Signal-to-Noise Ratio* (PSNR) under the network's power constraints across the physical, the data link and the application layer. Moreover, we are employing the Particle Swarm Optimization algorithm that does not require modifications of the original optimization problem.

Both cooperative and non-cooperative game theoretic frameworks have been proposed for efficient resource allocation in wireless networks following either a centralized or a distributed approach. Furthermore, various game-theoretic pricing schemes regulate the resource usage through a compromise between the users' desire to optimize their own performance and the network's general need for efficient resource allocation. In this context, a Nash equilibrium based power control method that assumes a wireless relay-assisted network is proposed in [15], where the users aim to optimize their transmission rate through the power allocation process, while the relay node aims at maximizing its total rate. The users make payments to the relay according to pre-specified prices that enhance the relay's gain, as they competitively adjust their transmission powers in order to increase the received signal-to-noise ratio. Another approach [16], also utilizes the Nash equilibrium with a joint pricing scheme in a *Code Division Multiple Access* (CDMA) based network, so that both the utilities of the users and the network utility are optimized. The users' utility comprises two factors related to the achieved throughput and the energy consumption, while the network utility reflects the network energy consumption.

Many cooperative schemes utilize the *Nash Bargaining Solution* (NBS) [17] to reach a beneficial single objective resource allocation for all nodes [4,6–8,11,13,18–20]. Cooperative resource allocation schemes are a promising approach for competitive wireless environments that require proportional fairness and resource allocation among the nodes. An approach based on NBS is applied on OFDMA *Cognitive Radio* (CR) networks [11] and optimizes the overall system throughput by assigning higher priority to primary CR users, while guaranteeing a minimum throughput for both primary and secondary CR users. The problem of fair resource sharing between two selfish nodes in cooperative relay networks is considered and solved by using NBS in [20]. An interesting two-stage approach that utilizes NBS to ensure fairness in the subcarrier and power allocation problem in a relayed uplink OFDMA system is proposed in [13]. Another work that formulates Nash bargaining assigns subcarriers, transmission powers and transmit precoders to the nodes of a multiple-input and multiple-output OFDMA system [19]. Furthermore, a bi-objective NBS-based framework was applied to allocate bandwidth for elastic services in high-speed networks with fairness and in a distributed manner, while maximizing the network revenue [21]. The previous work [4] was exclusively aiming