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Game-theoretic solutions through intelligent optimization for efficient resource management in wireless visual sensor networks

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A B S T R A C T

We propose a quality-driven cross-layer optimization scheme for wireless direct sequence code division multiple access (DS-CDMA) visual sensor networks (VSNs). The scheme takes into account the fact that different nodes image videos with varying amounts of motion and determines the source coding rate, channel coding rate, and power level for each node under constraints on the available bit rate and power. The objective is to maximize the quality of the video received by the centralized control unit (CCU) from each node. However, since increasing the power level of one node will lead to increased interference with the rest of the nodes, simultaneous maximization of the video qualities of all nodes is not possible. In fact, there are an infinite number of Pareto-optimal solutions. Thus, we propose the use of the Nash bargaining solution (NBS), which pinpoints one of the infinite Pareto-optimal solutions, based on the stipulation that the solution should satisfy four fairness axioms. The NBS results in a mixed-integer optimization problem, which is solved using the particle swarm optimization (PSO) algorithm. The presented experimental results demonstrate the advantages of the NBS compared with alternative optimization criteria.

1. Introduction

Wireless video communications suffer from a number of network resource constraints, including bandwidth, energy and computational complexity limitations. Data imaging, processing and transmission are recognized as power-consuming operations that can affect the performance of *visual sensor networks* (VSNs). Also, the available bit rate for video transmission can be limited in a wireless channel due to limited bandwidth and adverse channel conditions. VSNs consist of a number of spatially distributed nodes, each one equipped with a camera. The nodes are able to image and detect fields of different motion levels, depending on the specific application. The main challenge in VSNs is the coordinated behavior of each node constituting the network, such that it maximizes the overall system performance within the various resource constraints.

In general, game theory expands in two sharply different directions, namely non-cooperative game theory and cooperative game theory. The first branch is mainly concerned with the mutual interactions among intelligent individuals, striving to achieve their own goals. Several applications of non-cooperative game theory in wireless

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networks are provided in [1–4]. In all these works, the Nash equilibrium appears as the solution achieved when the players compete with each other. A Nash equilibrium is reached when the strategy of each player is the best response to the strategies of the other players. However, such selfish behaviors often lead to suboptimal solutions, in the sense that user collaboration could promote an improved outcome, favorable for all players of the game.

In5 cooperative game theory models, the players coordinate their strategies by forming coalitions, in order to agree on a mutually acceptable division of the payoff. This aspect of game theory is also used in wireless networks for obtaining unbiased and efficient resource allocation schemes, avoiding disproportional allocations or resource depletion. Cooperative game theory concepts have been used to solve the opportunistic spectrum access problem [5]. Also, the issue of multi-radio resource allocation in generic heterogeneous wireless networks has been addressed based on the idea of network technologies cooperation [6]. Moreover, bargaining theory, which is highly associated with cooperative game theory, was applied to distribute resources at a relay node to multiple source nodes [7]. In [8], the problem of downlink resource allocation for a multi-user multiple-input multiple-output orthogonal frequency division multiple access system was considered through the bargaining perspective, while different fairness policies targeting at efficient resource management have been proposed [9–11].

The different nodes of a wireless VSN image videos with varying amounts of motion. When the employed network access method is the *direct sequence code division multiple access* (DS-CDMA), all nodes can transmit at the same time, sharing the same available bandwidth. However, a node transmission causes interference to the transmissions of the other nodes, deteriorating the quality of the video they transmit. If a node captures a video with low motion, then it may use fewer bits for source coding (video compression). This will leave more bits available for channel coding. Stronger channel coding will allow the transmission to tolerate a higher bit error rate. Thus, the transmission power of that node may be lower.

On the other hand, if a node captures a video with high motion, it will use more bits for source coding and fewer bits for channel coding, thus requiring a higher transmission power. Aiming at the achievement of high video quality, the transmission power should be adequately high to permit reliable data transmission and maintain the quality of the video reception. On the contrary, given that sensor nodes are battery-operated systems, it needs to be low enough to enhance the battery life of the nodes and keep interference to the other nodes' transmissions to low levels.

Additionally, DS-CDMA systems are interference limited and do not have a fixed limit on the number of users that can access the channel. Hence, low-motion nodes that transmit at low power will cause limited interference with the rest of the nodes, thus maintaining good overall system performance and allowing a larger number of nodes to use the channel. Thus, our consideration of the level of motion in the captured videos in the optimization makes DS-CDMA a clear choice as a wireless multiple access system.

In our previous work [12], we proposed a cross-layer optimization algorithm, under a centralized setting [13–15], able to select the source coding rate, channel coding rate, and power level for each node, assuming constraints on the available bit rate and power. The objective was the maximization of the quality of the videos received by the *centralized control unit* (CCU) from each node. For this purpose, in [12] we used two optimization criteria; the *minimized average distortion* (MAD) criterion and the *minimized maximum distortion* (MMD) criterion.

As it is declared by their names, the MAD and MMD minimize the average and the maximum distortion of the nodes, respectively. Thus, they are rather focused on the overall or worst-case behavior of the network. Also, in [12], all parameters to be optimized (source coding rates, channel coding rates, power levels) assumed values from discrete sets. Therefore, a combinatorial optimization problem was formulated and solved. Furthermore, the MAD and MMD criteria were also used in [16], where the power levels assumed values from a continuous set, resulting in a mixed-integer optimization problem, which was solved using the *particle swarm optimization* (PSO) algorithm.

In [17], we applied axiomatic bargaining game theory [18], which belongs to the broader category of cooperative games. Axiomatic bargaining defines the properties (axioms) that shall be adhered to by the optimal solution, and they serve as criteria for rejecting other candidate solutions, until a unique optimal solution is finally selected. Specifically, in [17], we proposed the use of the *Nash bargaining solution* (NBS) in the game of resource allocation in a wireless VSN that uses DS-CDMA. In that work [17], the *disagreement point* (*dp*), which is the vector of minimum utilities that each node expects by joining the game without cooperating with the other nodes, was assumed to be the Nash equilibrium. Furthermore, finding the NBS involves solving an optimization problem where the Nash product is maximized. In the same paper [17], all parameters to be optimized (source coding rates, channel coding rates, power levels) were assumed to take values from discrete sets.

In the present paper, we apply cooperative game theory by using the Nash bargaining solution. The objective is to ameliorate the quality of the videos received by the CCU from each node, taking into account the fact that different nodes image videos with varying amounts of motion. Since the simultaneous maximization of the video qualities of all nodes is not possible, we employ the NBS in order to pinpoint one of the infinite Pareto-optimal solutions, based on the stipulation that the solution should satisfy four fairness axioms. Specifically, this solution promises fairness for all nodes, taking into account the amounts of motion in the videos they capture.

Compared to our previous work [17], the current paper deals with a mixed-integer optimization problem, since it involves both continuous (power levels) and discrete (source coding rates and channel coding rates) nodes' transmission parameters. Clearly, allowing power levels to take values from a continuous set offers flexibility to the CCU to perform better management of the nodes' transmission parameters, achieving in this way better end-to-end video quality for each node. Additionally, driven by the fact that, in a considered game, users' collaboration promotes improved outcomes favorable for all players participating in the game, in this work, we take careful treatment to the optimal setting