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Network lifetime optimization for wireless video sensor networks with network coding/ARQ hybrid adaptive error-control scheme

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ABSTRACT

This paper addresses the performance optimization of network lifetime and resource allocation for wireless video sensor networks. Network flow control and video encoding bit rate are jointly optimized, aiming to maximize the network lifetime at a given power budget and video quality requirement. We develop a generalized power consumption model for video sensors, in which video encoding, data communication and error-control behavior are completely considered. To combat packet loss over wireless channels, a hybrid error-control scheme integrating network coding and ARQ protocol is introduced. It adaptively adjusts the number of redundant coded packets according to ARQ feedbacks with a fixed code structure and decoding algorithm. Through the Lagrange dual and subgradient approach, a fully decentralized algorithm is proposed to solve the target convex problem. Finally, simulation results validate the convergence and performance of the proposed algorithm in a large-scale random topology as well as in a small static network.

1. Introduction

Wireless video sensor network (WVSN) is a special kind of wireless sensor network. It consists of geographically distributed video sensors, and is capable of capturing, processing visual information, and delivering them to the sink nodes for further analysis [1]. Typically, WVSNs have been envisioned for a wild range of important applications including security monitoring, emergence response, environmental tracking and health monitoring. In practice, battery-powered video sensors are often deployed in remote and unreachable locations. Therefore, minimizing power consumption to prolong the network lifetime and providing high-quality video are of paramount importance in WVSNs.

Over the past few years, energy conservation schemes for wireless sensor networks have been extensively studied [2–7]. Yang et al. in [2] proposed a mechanism that utilizes sensors' mobility to balance the energy consumption so as to extend the lifetime of the entire network. Zhao et al. [3] presented an optimal sensor scheduling and information routing scheme, in which the impacts of the network geometry and the energy consumption in communications are taken into account. Targeting at saving the aggregate transmit power, an SNR-constrained power reduction scheme is presented in [4]. These methods effectively reduce sensors' energy consumption, but fail to derive an optimal network lifetime.

From network performance perspective, the cross-layer design provides a promising approach for maximizing the network lifetime. A joint optimal design of the physical, medium access control (MAC), and routing layers is developed in [5]. It formulates the problem of optimal routing flow, link schedule, as well as link transmission powers as a non-linear optimization problem. The authors in [6] attempted to maximize the lifetime of energy constrained WSNs with a mixed integer convex optimization solution,

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where the time division multiple access (TDMA) mechanism is adopted in MAC layer, and the impacts of data rate, link access and routing are jointly considered. Also, the performance tradeoff between fair rate allocation and maximum network lifetime was investigated in [7].

The power consumption model adopted in existing research is constructed on the basis of conventional wireless sensor networks, where the data processing function at the sensor node is very simple and the corresponding power consumption is assumed to be negligible. In WVSN, the raw video of high rate is required to be compressed before being injected onto the channel. In this case, energy utilized in video encoding is significant and cannot be neglected anymore.

The power consumption on video encoding and data transmission are intuitively paradoxical. If the encoding process occupies too much energy, the power left for the transmission process will decrease, thus deteriorating the received video quality. On the other hand, if the power budget for data transmission is raised, the power consumption on video encoding will be curtailed, which will definitely influence the quality of the gathered video. A power-rate-distortion (P-R-D) model that characterized the relationship between power consumption of video encoding and its rate-distortion (R-D) performance, was developed by He et al. in [1]. Following this model, a distributed algorithm for maximizing the network lifetime of WVSNs is proposed in [8]. The scenario it considered is very simple where not only the channel capacity is assumed unlimited, but the channel interference is negligible. How to balance encoding power, rate and distortion, meanwhile, make a joint optimization with network lifetime have remained vastly unexplored in WVSNs.

Reliable communication over time-varying and error-prone wireless channels currently is still challenging. Automatic repeat request (ARQ) and forward error correction (FEC) are two popular error-control mechanisms. ARQ adopts feedback and retransmission scheme, thus is not suited for delay-sensitive video applications [9]. Packet-level FEC, (e.g., Reed-Solomon Erasure (RSE) code [10]), which deals with erasures instead of bit errors, is more suitable to reliable communication over wireless networks [11,12]. In most FEC-based schemes, the maximum error-control redundancy is upper-bounded by the FEC-code symbol size, which may still lead to decoding failures when the channel loss probabilities increase tremendously [13]. Choi et al. [14] proposed a class of adaptive error-control schemes, in which the number of FEC code segments and the frame length are chosen adaptively based on the estimated channel condition. However, different encoding/decoding structures are required for various redundancy levels. And the implementation complexity is too high to be applicable to real systems. Furthermore, many FEC schemes have been investigated in a hop-by-hop fashion that requires each relay to execute both decoding and encoding operation [8]. Such power consumption is magnificent and becomes impossible in large-scale WSVNs.

Recently, the combination of network coding with multipath routing [15,16] has exhibited some unique advantages in coping with the unreliability: (1) It can be performed in a decentralized way, requiring no coordination among nodes; (2) It can be operated ratelessly, i.e. it can run indefinitely until successful decoding. (3) Flows of linearly independent, instead of same copies traversing multiple paths may reduce the transmission redundancy [17]. In this study, we will develop a network coding/ARQ hybrid error-control scheme with low implementation complexity and high throughput efficiency. It can dynamically adjust the error-control redundancy levels according to the instantaneous channel condition.

The motivation of this paper is to address the performance optimization of network lifetime and resource allocation for wireless video sensor networks. Our main contributions are as follows. First, absorbing the generalized power consumption model of network coding in our previous work [18], we construct a power consumption model for video sensors, in which video encoding, data communication and error-control behavior are completely considered. Second, we propose a joint optimization of video coding rate, aggregate power consumption and flow control to maximize the network lifetime and meet video quality requirements. To combat packet loss over wireless channels, a hybrid error-control scheme integrating network coding and ARQ protocol is introduced. It adaptively adjusts the number of redundant coded packets according to ARQ feedbacks with a fixed code structure and decoding algorithm. Last, using Lagrange dual and subgradient approach, we solve the target convex optimization problem in a fully decentralized manner, and evaluate its performance in a large-scale random topology as well as in a small static network.

The rest of the paper is organized as follows: Section 2 defines the system model and related network constraints. Section 3 presents the proposed hybrid error-control scheme. Section 5 formulates the optimization problem of network lifetime and rate allocation, and proposes a fully decentralized algorithm over lossy wireless channels. Finally, simulation results are presented in Section 6.

2. System modeling

2.1. Network model

A static wireless video sensor network can be modeled as a directed graph $G(V,E)$, where V is the set of sensor nodes and E is the set of directed links between nodes. The set V consists of two disjoint subsets S and $T(V = S \cup T)$, representing video sensor nodes and sink nodes respectively. Sensor nodes perform video capture, video encoding and packets routing, while sink nodes are destinations of WVSN. All sensor nodes have a maximum transmission range d_x. So a directed link $(i,j) \in E$ exists between node i and node j if their distance d_{ij} satisfies $d_{ij} \leqslant d_x$. Suppose there are multiple alternative paths $J(s)$ existed between sensor node s and the sink node. And each node s is associated with a matrix H^s to reflect the relationship between its paths and related links. Let $H_{ij}^{sm} = 1$ if path $m \in J(s)$ of sensor node s uses link (i,j), or else $H_{ij}^{sm} = 0$.