Journal of Network and Computer Applications 82 (2017) 65–76

Contents lists available at ScienceDirect

Journal of Network and Computer Applications

journal homepage: www.elsevier.com/locate/jnca

Distributed in-network processing and resource optimization over mobile-health systems

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ARTICLE INFO

Keywords:
Convex optimization
Decomposition
Distributed algorithm
EEG signals
Cross-layer design
M-health system

ABSTRACT

Advances in wireless and mobile communication technologies has promoted the development of Mobile-health (m-health) systems to find new ways to acquire, process, transport, and secure the medical data. M-health systems provide the scalability needed to cope with the increasing number of elderly and chronic disease patients requiring constant monitoring. However, the design and operation of such systems with Body Area Sensor Networks (BASNs) is challenging in twofold. First, limited energy, computational and storage resources of the sensor nodes. Second, the need to guarantee application level Quality of Service (QoS). In this paper, we integrate wireless network components, and application-layer characteristics to provide sustainable, energy-efficient and high-quality services for m-health systems. In particular, we propose an Energy-Cost-Distortion solution, which exploits the benefits of in-network processing and medical data adaptation to optimize the transmission energy consumption and the cost of using network services. Moreover, we present a distributed cross-layer solution, which is suitable for heterogeneous wireless m-health systems with variable network size. Our scheme leverages Lagrangian duality theory to find efficient trade-off among energy consumption, network cost, and vital signs distortion, for delay sensitive transmission of medical data. Simulation results show that the proposed scheme achieves the optimal trade-off between energy efficiency and QoS requirements, while providing 15% savings in the objective function (i.e., energy-cost-distortion utility function), compared to solutions based on equal bandwidth allocation.

1. Introduction

Providing decent healthcare services for the chronically ill and elderly people becomes a top national interest worldwide. The rising number of chronic disease patients, emergency and disaster management, which require continuous monitoring of human vital signs, have increased the importance of remote monitoring and mobile-health (m-health) systems. Such systems emerge as a promising approach to improve healthcare efficiency, where miniaturized wearable and implantable body sensor nodes and smartphones are utilized to provide remote healthcare monitoring in many situations like disaster management and early detection of diseases (Panayides et al., 2013; Niyato and Camorlinga, 2009). In our work, we focus on the Electroencephalography (EEG)-based applications. The EEG signal is considered as the main source of information to study human brain, which plays an important role in diagnosis of epileptic disease, brain death, tumors, stroke and several brain disorders (Adeli et al., 2007). EEG signals also play a fundamental role in Brain Computer Interface (BCI) applications (Kottaimalai et al., 2013). In our model, the Personal/Patient Data Aggregator (PDA), potentially represented by a smartphone, gathers sensed data from a group of sensor nodes, and then forwards the aggregate traffic to the M-Health Cloud (MHC). In this scenario, the patients equipped with smartphones and body area sensor networks (BASN) can walk freely while receiving high-quality healthcare monitoring from medical professionals anytime and anywhere.

Although m-health systems have prominent benefits, they also exhibit peculiar design and operational challenges that need to be addressed. Among these are energy consumption, network performance, and quality of service (QoS) guarantee for the delivery of medical data. For example, in normal conditions, the medical patient's data is reported to the MHC every 5 min (Yuce et al., 2007). However, in case of emergency, the BASN starts reading a variety of medical measurements, hence, a large amount of data will be generated in a very short period of time. Furthermore, the sensed data should be reported every 10 s for high-intensive monitoring (Lu et al., 2013). Thus, it is clear that in these cases, the smartphone energy consumption and the management of the overall network in a distributed fashion becomes of prominent importance. Additionally, scalability and robustness against changes in topology (i.e., adding new nodes or node failure) are important design issues in m-health systems. All these factors make centralized approaches not appropriate for being used in real world situations, especially over large networks, and point to the need of simple, efficient, and distributed algorithms.

http://dx.doi.org/10.1016/j.jnca.2017.01.014
Received 25 September 2016; Received in revised form 26 October 2016; Accepted 15 January 2017
Available online 18 January 2017
1084-8045/

In addition to that, recording, processing, and transmitting large volumes of such data is challenging and may deem some of these applications impractical, especially for the increasing number of chronic disease patients that require continuous monitoring in highly populated cities. This has led to the emergence of smart health (s-health) concept, which is the context-aware evolution of m-health, leveraging mobile technologies to provide smart personalized health (Roy et al., 2016). This rising evolution of intelligent systems, mobile communications, and s-health services has motivated us to leverage context-aware in-network processing at the PDA on the raw EEG data prior to transmission, while considering application characteristics, wireless transmission dynamics, and physical layer resources.

Accordingly, in this paper, we propose a solution that enables energy-efficient high-quality patient health monitoring to facilitate remote chronic disease management. We propose a multi-objective optimization problem that targets different QoS metrics at the application layer like signal distortion, and at physical layer like transmission delay and Bit Error Rate (BER), as well as monetary cost and transmission energy. In particular, we aim to achieve the optimal trade-off among the above factors, which exhibit conflicting trends. The main contributions of our work can be summarized as follows:

(1) We design a system for EEG health monitoring that achieves high performance by properly combining network functionalities and EEG application characteristics.
(2) We formulate a cross-layer multi-objective optimization model that aims at adapting and minimizing, at each PDA, the encoding distortion and monetary cost at the application layer, as well as the transmission energy at the physical layer, while meeting the delay and BER constraints.
(3) We use geometric program transformation to convert the aforementioned problem into a convex problem, for which an optimal, centralized solution is obtained.
(4) By leveraging Lagrangian duality theory, we then propose a distributed solution. The dual decomposition approach enables us to decouple the problem into a set of sub-problems that can be solved locally, leading to a distributed algorithm that converges to the optimal solution.
(5) The proposed distributed algorithm for EEG based m-health systems is analyzed and compared to the centralized approach. Our results show the efficiency of our distributed solution, its ability to converge to the optimal solution and to adapt to varying network conditions.

The rest of the paper is organized as follows. Section 2 discusses the related work while highlighting the novelty of our study. Section 3 introduces the system model and the problem formulation. Section 4 presents the proposed Energy-Cost-Distortion optimization problem. Section 5 presents an efficient distributed approach for solving the proposed problem. Section 6 presents the simulation environment and the obtained results. Finally, Section 7 draws our conclusions.

2. Related work

The investigated approaches in the field of m-health can be broadly classified into five categories: energy efficient BASNs design, wireless transmission resource allocation and optimization, implementation of smartphone health monitoring and BCI applications, efficient low-power hardware designs, as well as signal compression, feature extraction, and classification algorithms. Among different factors, energy efficiency in BASNs, and in general m-health systems, is one of the most challenging problems due to the requirements for high QoS and low transmission delay given the resource constraints. Many of the existing studies focus on Routing, MAC, and Physical layer design to address energy and power issues (Chen et al., 2011). The basic idea of these techniques is to design new communication methods that obtain optimal performance under the resource constraints. For example, authors in (Incel et al., 2011) present a multi-channel MAC protocol (MC-LMAC) that is designed for maximizing system throughput. MC-LMAC combines the advantages of interference-free and contention-free parallel transmissions on different channels. However, the overhead added by this solution is high, and the channel/slot utilization is low for low data rates. The authors in (Otal et al., 2009) develop a MAC model for BASNs to fulfill the desired reliability and latency of data transmissions, while simultaneously maximizing battery lifetime of individual body sensors. In (Jain et al., 2012), the authors studied the energy-distortion trade-off from the information-theoretic point of view, in the context of various joint source-channel coding problems.

Wireless transmission resource optimization in m-health systems has also been widely investigated. For instance, authors in (He et al., 2011) analyze the relationship between the source rate and the uninterrupted lifetime of a sensor. They formulate a steady-rate optimization problem to minimize rate fluctuation with respect to average sustainable rate. Moreover, they minimize the transmission power of the data aggregators, subject to some power constraints, the requirements on packet loss rate, transmission BER, and packet delay. However, they neither consider the signal processing part in their model nor take the application characteristics into consideration. In addition to that, the growing power requirements and the need for green communications motivate developing energy efficient techniques to minimize power consumption in next-generation wireless networks, while meeting high user's QoS expectations (Andrews et al., 2014). In this context, the authors in (Trestian et al., 2013) propose a hybrid multimedia delivery solution, which achieves an energy-quality-cost trade-off by combining an adaptive multimedia delivery mechanism with a network selection solution. Based on user preferences, location-based and network related information, the proposed solution in (Trestian et al., 2013) determines whether to adapt multimedia delivery or handover to a new network by computing a score function for each of the selected candidate networks. Then, it selects the network with the highest score as the target network. In (Wu et al., 2014), the authors focus on the energy efficient design of physical-layer transmission technologies and MAC-layer radio resource management. They study the trade-off between spectrum efficiency and energy efficiency as part of their optimization model. Some studies have also focused on joint compression and communication optimization, where the compression power consumption and transmission power consumption are jointly considered in order to optimize the performance of the entire system. However, this approach is mainly applied to video transmission systems, since the video encoding itself consumes high power compared with the wireless transmission (Zhang et al., 2009). In general, it is agreed that energy-efficient cross layer design is a very complex problem, since it requires to effectively investigate all the network layer optimizations jointly (Ma et al., 2013).

The immense advancements in smartphone features and capabilities have promoted the development of smartphone application (app) for long-term chronic condition management. Health-related smartphone apps can build a sense of security for patients with chronic conditions, since they felt secure that their states are carefully monitored, and their doctors take care of them even outside the hospital or clinic. Thus, there is a growing interest in the literature in leveraging mobile apps to enhance healthcare services for chronically ill and elderly people. For instance, the authors in (Aydn et al., 2016) have implemented an embedded low-cost, low power web server for internet based wireless control of BCI based home environments. This web server provides remote access to the environmental control module through transmitting BCI output commands determined by BCI system to drive the output devices. In (Isik et al., 2013), the authors present a real-time mobile adaptive tracking system, where the wireless local area network, or third-generation-based wireless networks are used to transfer test results from a smartphone to the remote database. This system provides real-time classification of test results,