Computer Networks 74 (2014) 64–77

Contents lists available at ScienceDirect

Computer Networks

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

Interference-aware energy-efficient cross-layer design for healthcare monitoring applications

Alaa Awad [a], Amr Mohamed [a,*], Amr A. El-Sherif [a,b], Omar A. Nasr [c]

[a] Department of Computer Science, Qatar University, Doha, Qatar
[b] Department of Electrical Engineering, Alexandria University, Egypt
[c] Department of Electronics and Communications, Cairo University, Egypt

ARTICLE INFO

Article history:
Received 9 February 2014
Received in revised form 15 August 2014
Accepted 3 September 2014
Available online 16 September 2014

Keywords:
BASNs
EEG signals
Convex optimization
Cross-layer optimization

ABSTRACT

Body Area Sensor Networks (BASNs) leverage wireless communication technologies to provide healthcare stakeholders with innovative tools and solutions that can revolutionize healthcare provisioning; BASNs thus promotes new ways to acquire, process, transport, and secure the raw and processed medical data to 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 BASNs is challenging, mainly due to the limited power source and small form factor of the sensor nodes. The main goal of this paper is to minimize the total energy consumption to prolong the lifetime of the wireless BASNs for healthcare applications. An Energy–Delay–Distortion cross-layer framework is proposed in order to ensure transmission quality for medical signals under limited power and computational resources. The proposed cross-layer framework spans the Application–MAC–Physical layers. The optimal encoding and transmission energy are computed to minimize the total energy consumption in a delay constrained wireless BASN. The proposed framework considers three scheduling techniques: TDMA, TDMA–Simultaneous Transmission and dynamic frequency allocation scheduling. The TDMA–ST scheme schedules the weakly interfering links to transmit simultaneously, and schedules the strongly interfering links to transmit at different time slots. The dynamic frequency allocation scheme allocates the time–frequency slots optimally based on the application's requirements. Simulation results show that these proposed scheduling techniques offer significant energy savings, compared to the algorithms that ignore cross-layer optimization.

1. Introduction

The rising number of chronic disease patients, emergency and disaster management, that require continuous monitoring and analysis of human vital signs, have increased the importance of continuous monitoring and mobile health systems. Furthermore, advances in wireless communication technologies and biosensors have resulted in viable body area network applications that boost the opportunity for ubiquitous real-time healthcare monitoring without constraining the activities of the patient.

Wireless BASN consists of implantable or wearable sensors in, on, or close to human body (e.g. electrocardiogram (ECG) and electroencephalogram (EEG) sensors) to monitor vital signs such as body temperature, activity or heart-rate. These sensors continuously monitor vital signs and send the gathered data to a powerful external device, such as

* Corresponding author.
E-mail addresses: aawad@qu.edu.qa (A. Awad), amrm@qu.edu.qa (A. Mohamed), amr.elsherif@ieee.org (A.A. El-Sherif), omaranasr@ieee.org (O.A. Nasr).

http://dx.doi.org/10.1016/j.comnet.2014.09.003
1389-1286/

a Personal/Patient Data Aggregator (PDA) or a cell phone, which forwards the aggregate traffic to a central server. Finally, the health data are sent to the physician via wireless connections and the Internet. Therefore, BASN is considered as a promising networking solution for health monitoring system, which helps to detect, evaluate, and diagnose various diseases. However, the large-heavy batteries should not be used in a device designed to be worn by patients, and thus minimizing average power dissipation is one of the key challenges in this technology. In this paper, we propose a resource-aware cross-layer architecture to support reliable and energy-efficient data transmission, especially for wireless EEG data monitoring.

1.1. Related work

Energy efficiency in wireless sensor networks (WSNs) has gained significant research interests recently. In MAC layer, contention-based approaches (e.g. carrier sense multiple access with collision avoidance (CSMA/CA)), schedule-based approaches (e.g. Time Division Multiple Access (TDMA)) and scheduled-contention approaches are the major categories of current protocols designed for WSNs. The advantages of contention-based approaches are the simplicity, no need for central point of coordination, and adaptation to traffic load. However, they are not energy efficient due to idle listening, overhearing, and possibility of packets collision [1]. Based on topology and limited number of nodes in BASNs, TDMA could be considered as the most suitable solution for medium access in BASNs [1]; because of its collision-free, high reliability, and deterministic transmission features. However, it has strict synchronization requirements that may cause additional energy consumption [2]. In [3], the authors presented a Heartbeat Driven MAC (H-MAC) protocol for BASNs which aims to improve energy efficiency by using heart beat rhythm information, extracted from an ECG signal, for synchronization of nodes. However, this MAC protocol does not support sporadic events and heartbeat rhythm information varies depending on conditions of the patient, so it may not always give suitable information for synchronization. The scheduled-contention approach is considered as a combination of scheduling and contention based approaches [4].

Parallel data transmission has also attracted attention as a transmission choice for BASNs. Thus, it became desirable to devise multi-channel MAC protocols that handle bursty traffic [5]. The idea of simultaneous transmission has also been used recently in Wireless Mesh Networks (WMNs) as a transmission scheme. The authors in [6] adopted the idea that nodes three hops away can occupy the same slot to reduce the time of data transmission. This transmission scheme reduces the delay of the whole network. The authors in [7] use simultaneous transmissions, as long as they satisfy the underlying interference constraints, to get a lower bound on the delay performance. They used the 2-hop interference model, where any two simultaneous-active links are always separated by two or more hops in the underlying network graph. However, due to using the same channel and the simultaneous data transfer, the network capacity and the performance of WMNs may degrade significantly because of the interference [8].

As there is an inherent interdependence between the layers of the protocol stack, the cross-layer strategies can significantly improve the performance through adaptive transmission and resource allocation schemes corresponding to application requirements and environment dynamics. From [9], it can be seen that cross-layer design plays a key role in reducing the total energy consumption. The design challenges and the importance of cross-layer design for meeting application requirements in energy constrained ad-hoc wireless networks were also described in [10].

On the other hand, much of the research in the area of BASNs has focused on issues related to wireless sensor designs, sensor miniaturization, signal compression techniques and low-power hardware design [11–14]. A good review of the state-of-the-art hardware, technologies, and standards for BASN was presented in [15]. For example, the authors in [16] investigate the properties of compressed ECG data for energy saving using a selective encryption mechanism and a two-rate unequal error protection scheme. Other researches focus on reducing power consumption at the MAC layer by avoiding idle listening and collisions [17], or by presenting latency-energy optimization [18].

The previous work discussed above ignored the cross-layer design which optimizes the performance by jointly considering multiple protocol layers. To the best of our knowledge, the cross-layer design of energy minimization to address distortion constraints for delay sensitive transmission of EEG traffic in BASNs has not been studied before. Therefore, in our previous work [19], we have analyzed the transmission and processing energy consumption and developed an Energy–Compression–Distortion (E–C–D) analysis framework. This framework extends the traditional distortion analysis by including the energy consumption dimension. Using this framework, a cross-layer optimization model that aims at minimizing the total energy consumption, under a TDMA scheduling, is proposed. Furthermore, for energy-efficient bandwidth allocation, we proposed a dynamic frequency allocation scheme in [20]. This allocation scheme reduces the energy consumption compared to the conventional TDMA scheme that assumes constant bandwidth allocation. In this paper, however, we overcome the non-convexity problem of the original model by formally transforming it into a problem of geometric programming (GP) [21], which helps design exact and efficient solutions using convex optimization techniques.

1.2. Contributions

We target the minimization of the total energy consumption in the BASN. Two major components contribute to this energy minimization: transmission energy and processing/encoding energy. Hence, different parameters are optimized across the application, MAC and physical layers to optimize and adapt the transmission energy in physical layer and the encoding energy in application layer, while satisfying the basic requirement of quality of service