Computer Networks 75 (2014) 351–366

Contents lists available at ScienceDirect

Computer Networks

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

Optimal energy efficient packet scheduling with arbitrary individual deadline guarantee

Feng Shan [a,*], Junzhou Luo [a], Xiaojun Shen [b]

[a] School of Computer Science and Engineering, Southeast University, Nanjing, Jiangsu 210096, China
[b] School of Computing and Engineering, University of Missouri-Kansas City, Kansas City, MO 64110, USA

ARTICLE INFO

Article history:
Received 30 November 2013
Received in revised form 18 May 2014
Accepted 22 October 2014
Available online 29 October 2014

Keywords:
Energy efficiency
Rate control
Wireless communication
Densest interval first
Deadline guarantee
Scheduling algorithm

ABSTRACT

Given a rate adaptive wireless transmitter, a challenging problem is to design a rate control policy for it such that the energy consumption is minimized at transmitting a set of dynamically arrived pack2;ets with arbitrary individual deadlines. In a decade, researches have partially made progress on this topic. A latest work offers an optimal algorithm that allows packets to have arbitrary deadlines but requires them to follow the order they arrive. This paper first presents the Densest Interval First (DIF) policy which repeatedly locates the densest data interval and determines its transmission rate. This policy is proved to be optimal for the most general model that allows arbitrary arrival times as well as arbitrary deadlines. Then, this paper presents a simple EDF (earliest deadline first) algorithm to actually schedule the transmission time for each packet. It is proved that the EDF always guarantees every packet to complete transmission before its deadline with minimum energy consumption which is computed and required by DIF. Finally, this paper also proposes a novel online policy named Density Guided Cooling (DGC) policy which models Newton's Law of Cooling. Simulations show that online DGC policy constantly produces a rate scheduling that on average consumes energy within 110% of the minimum value obtained by the offline DIF.

1. Introduction

Most wireless networks, e.g., sensor networks, ad hoc networks and cell networks, rely upon limited energy supply such as batteries to support their operations. Therefore, how to efficiently use the limited energy is a crucial issue in all aspects of the network design and operations, which often determines the length of wireless devices' working period or the network lifetime. Tremendous research efforts have been made in designing energy efficient routing, energy efficient data gathering, etc.

Because very often packets from various real-time applications that have different arrival times and different delay constraints need be transmitted through a common channel, a challenging research task is to develop a transmission rate control policy and a scheduling algorithm such that a minimum energy is used in transmitting all arrived packets before their deadlines.

1.1. Related work

Prabhakar, Uysal-Biyikoglu, and El Gamal are among the first group of researchers who formulated the energy efficient packet transmission problem more than a decade ago ([1] and its extension [2]), which has drawn considerable interests from researchers in the field of wireless communications. In [1,2], they considered an offline case

* Corresponding author.
E-mail addresses: shanfeng@seu.edu.cn (F. Shan), jluo@seu.edu.cn (J. Luo), shenx@umkc.edu (X. Shen).

http://dx.doi.org/10.1016/j.comnet.2014.10.022

where the arrival time and size of every packet are known prior to the scheduling and all packets have a common deadline. They presented an optimal scheduling algorithm that guarantees to deliver all packets before the deadline with minimum energy consumption. In their proof, several important optimality properties were introduced which are useful and inspiring for following researches. Uysal-Biyikoglu and El Gamal [3] also generalized the problem by taking multiple-access channels and channel fading into consideration. They proposed the *FlowRight* algorithm to find an optimal offline schedule for the generalized problem but still assumed that all packets have a common deadline. As pointed out by Chen et al. [4,5], the single deadline model does not explicitly consider individual packet delay performance.

In [6], Khojastepour and Sabharwal started to look at the energy efficient packet transmission problem where each packet could have its own deadline. They proposed the *water-filling* method to find an optimal rate control policy. However, this method is applicable only for the case where all packets have arrived and have been waiting in buffer before scheduling. Obviously, this is an easy case but a good initial work for dealing with individual packet deadlines.

The energy efficient packet transmission problem with individual packet deadlines has also been studied by other researchers. Chen et al. ([4] and journal version [5]) proposed an offline optimal scheduling algorithm that handles individual deadlines. However, a restriction was imposed that all packets must have equal delay constraints which means that the length of time interval from the arrival time to its deadline is the same for every packet. Later, they extended the algorithm to an online algorithm [7] and then to a fading channel ([8] and journal version [9]). Although the authors claimed the result can be extended to scenarios with unequal delay constraints, it seems not an easy job.

Zafer and Modiano ([10] and journal version [11]) presented an optimal algorithm that allows each packet to have an arbitrary size, an arbitrary arrival time and an arbitrary deadline. They claimed that earlier results on the energy efficient packet transmission problem can be recovered as special cases. They used cumulative curves to trace packet arrivals and packet departures. The key observation is that a feasible departure curve always lies between the arrival curve and minimum departure curve. Displayed in the cumulative data-time diagram, their idea is intuitive and easy to understand. Later, they extended their results by considering fading effects [12]. Their work has made a true progress on the energy efficient packet transmission problem. However, they still need to make an undesirable assumption that a packet arriving earlier carries an earlier deadline. In other words, the cumulative curves fail to handle the case where a packet arrived later may have a more urgent deadline.

In addition to above research results that are directly related to our paper, some important extended work is also observed. For example, recently, Yang and Ulukus [13] investigated the energy efficient packet transmission problem in an energy harvesting system where the energy used by the transmitter can get recharged, time by time, to support long life operation. However, it is still necessary to consider how to control the transmission rate to minimize energy consumption because the recharged energy is limited each time and the amount of data to be transmitted may be large. They assume that the time and amount of energy received from each harvesting are known in advance and the size and arrival time of each packet are also known in advance. There is no deadline considered, but they presented an optimal algorithm that guarantees to finish transmission of all data in a shortest time span. Later the result for a single channel was extended to the case of multi-access channels [14], to the case of broadcasting channels [15,16], and to the case with fading channels [17,18]. Interested readers may find more related work such as [19–21]. We omit details here.

Most papers we introduced above also provided online algorithms [1–3,7–9,11,18] as an extension of their offline algorithms. Basically, they follow more or less a similar approach, that is, based on current known information, use the offline algorithm to set transmission rates until a new packet arrives. When a new packet arrives, the online algorithm re-calculates the best rates using the offline algorithm.

1.2. Contributions

We can conclude from the above related works that an unsolved challenging open problem in the past 10 years is how to design an optimal energy efficient rate control policy for a single channel for transmitting a sequence of packets each of which has an arbitrary individual arrival time, arbitrary size and arbitrary individual deadline. The technique of cumulative curves seems not applicable to this more general model. We need a new method. Our contributions can be summarized as follows.

1. We have solved the above open problem. An optimal rate control policy named *Densest Interval First* (*DIF*) is presented, which is inspired by the YDS algorithm proposed by Yao et al. [22].
2. The DIF approach opens a new avenue to obtaining optimal results for other similar rate adaption problems in fading channels, energy harvesting systems, multi-channel systems, etc. in the future.
3. We prove that, once the transmission rate for each time interval is determined by DIF, the Earliest Deadline First (EDF) scheduling algorithm produces an actual schedule for each individual packet to complete its transmission before its deadline with the minimum energy allowed by DIF.
4. We also present an online policy called Density Guided Cooling (DGC) policy that models Newton's Law of Cooling. Simulations show that this policy constantly produces a rate scheduling that on average consumes energy within 110% of the minimum.

The YDS algorithm [22] is designed to solve task-scheduling problems for processors, in which tasks may have arbitrary arrival time and arbitrary deadline. The YDS algorithm inspired us to design the DIF policy, which solves the 10-year open question in wireless communication. Although the two methods share some similar idea, the