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Data bundling for energy efficient communication of wearable devices☆

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ABSTRACT

The amount of data that wearable devices send and receive is rapidly increasing and exceeds the capacity of the energy efficient link technologies (e.g., Bluetooth Low Energy). High capacity wireless link typically requires high connection setup cost, while wearable devices are intrinsically equipped with small battery. To deal with this dilemma, we propose to aggregate multiple data transmission requests into a single chunk and send the aggregated chunk at once to reduce the energy consumption for connection setup. Where this concept of 'data bundling' has been used for cloud storage services, we apply this concept to wearable devices. Data bundling extends the data delivery delay and therefore it is suitable to the applications that do not require strict real-time delivery. In this paper, we initially focus on reducing the energy consumption and then consider the tradeoff relationship between energy reduction and the penalty caused by the bundling delay. We design three bundling schemes and implement them in a commercial smartwatch which is connected to a smartphone via Bluetooth Classic link. The effectiveness of the proposed schemes is experimentally demonstrated and useful insights on the characteristics of bundling are discovered.

1. Introduction

Due to smaller battery capacity, wearable devices are much more energy constrained than larger devices like smart phones. For this reason, currently most wearable devices adopt Bluetooth as the primary communication link. Many wearable devices support two modes of Bluetooth, which are Bluetooth Classic (BTC) and Bluetooth Low Energy(BLE) (i.e., BT 4.0 dual-mode). In general, BLE consumes far less energy than BTC. According to [2], the energy consumption of BLE ranges from 1/2 to 1/100 of that of BTC, but the link throughput of BLE is considerably lower than BTC. While the typical function of wearable devices is information collection (e.g., biosensor data [3]) and information display/alarm (e.g., email notification [4]), other types of functions are emerging fast [4–6]. Some wearable devices are equipped with longer range radio such as WiFi and 3G cellular. Longer range Bluetooth link is about to be commercially available [7]. As the functionality of wearable devices expands, the energy consumption for communication becomes a key challenge.

For wireless communication, connection establishment needs to be done before actual data transmission, which is followed by post processing (including the 'tail' state). However such extra steps before and after data transmission consume substantial energy particularly for longer range radio like 3G. For example, the energy consumption to transmit a packet in 3G is measured to be about 3.5 J for actual transfer and 7.8 J for the extra steps [8]. The energy efficiency of Bluetooth is also significantly affected by this extra steps. In [9,10], it is reported that the energy consumption to transmit a packet in BTC is 94 mJ for actual transfer and 560 mJ for the extra steps. For BLE, the energy consumption to transmit a packet in BLE is 7.95 μJ for the actual transfer and 48.6 μJ for the extra steps [11,12]. Consequently, the total energy consumption for communication is dependent not only on the amount of data but also on the number of connection establishments. The main idea that we propose in this paper is to 'bundle' multiple data transmissions and transmit the aggregated data chunk at once in order to reduce the number of connection establishment. Bundling inevitably leads to the extension of data delivery delay due to buffering for aggregation. Except some real-time applications, most applications can tolerate additional delay to a certain degree.

Meanwhile the amount of data to be aggregated is a factor to affect the total energy consumption. The amount of data can be reduced via compression techniques such as differential compression and header/payload compression. For the synergy between

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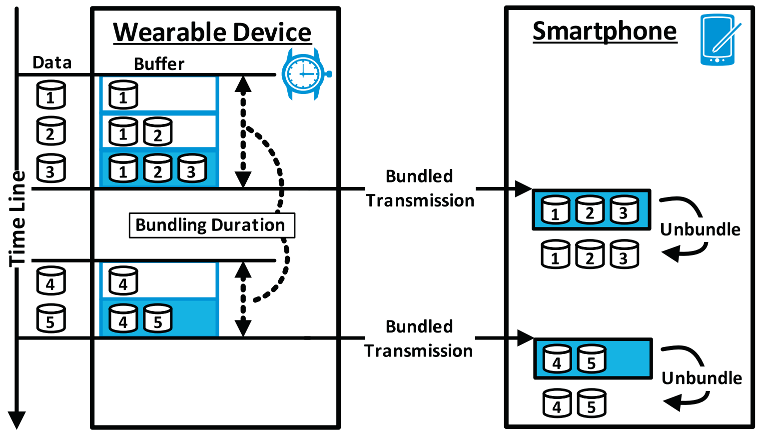

Fig. 1. Data bundling for wearable device.

bundling and the compression, our bundling idea can be extended with the compression techniques in terms of reducing the amount of data to be aggregated.

Fig. 1 illustrates the target scenario of this paper. We consider the Bluetooth communication between a wearable device and a smartphone, but the proposed scheme is applicable to other types of communication links. At the sender side, all the data transmission requests during the 'bundling duration' are gathered and the bundled data is transmitted at the end of the bundling duration. At the receiver side, the received data chunk is unbundled to obtain the original packets. While bundling may be applied for both directions, but we focus on the transmission originated by wearable devices in this paper as the focus is given to the energy efficiency of wearable devices. The key issue is the determination of the bundling duration. A simple approach is to use a fixed bundling duration, which we call a *Fixed Bundling* scheme. It is effective when data arrival follows a known regular pattern, but this approach will be inefficient for irregular traffic pattern. In this paper, we propose to adjust the bundling duration at runtime according to the unknown and irregular traffic pattern. Our algorithms can deal with diverse traffic patterns produced by heterogeneous applications running simultaneously in a wearable device.

The concept of data bundling has been widely used for cloud storage services. In [13], how bundling can reduce traffic overhead and improve the throughput for Dropbox is analyzed. The technique used for Dropbox is the *Fixed Bundling* scheme. In [14], the performance of various commercial personal cloud services is evaluated by considering 'bundling' as a key technique for reducing traffic overhead. In [15], bundling is studied from the viewpoint of *timer-triggered synchronization*. It concludes that there is no optimal algorithm which can cover all data patterns. On the basis of the work in [15], an update-batched synchronization algorithm is proposed in [16]. It waits for a certain duration or until the total size of data collected exceeds a certain threshold before transmitting the bundled data. All the existing works on bundling for cloud storage do not consider the energy efficiency.

The concept of bundling has been exploited for energy efficiency of mobile devices in cellular networks. A scheme for reducing the high tail energy consumption in 3G network is proposed in [8]. It bundles the transmission requests until the delayed transmissions do not violate the user-defined deadlines. In [17], an algorithm to coordinate transmission requests is proposed, which exploits the delay tolerance of multiple applications by using the ski-rental model. While these works are related to our scheme, they are not readily applicable to our target scenario because the tail time of Bluetooth is much shorter than that of 3G link [8].

In [18], bundling is applied for energy efficiency of smart phones in the context of instant messaging applications in 3G networks. The instant messaging applications exchanges the presence information periodically or in event-driven manners, and the smartphone awakes whenever the exchange occurs, which causes high energy consumption. This scheme utilizes a proxy server which bundles the exchange of presence information in a similar way to the *Fixed Bundling* scheme. Later the proxy server transfers the gathered data to the smartphone. This mechanism is designed for a specific application.

The use of bundling has been proposed for the traffic offloading from 3G to WiFi as well. In the scheme proposed in [19], the applications' tolerance to delay is estimated, and then based on this knowledge data transmission is delayed until WiFi is available in order to reduce the use of expensive 3G link. The feasibility of exploiting delay-tolerance in WiFi offloading is theoretically analyzed by some literatures [20–22].

In [23], computation offloading is empirically studied for a wearable device, Google Glass. In this paper, computation offloading from wearable to smartphone or from wearable to cloud via smartphone is considered. They measure the time and the energy consumption for a specific computation task. The study concludes that computation offloading is beneficial when the amount of computation is sufficiently large to justify the overhead occurring for offloading. While this study has different aims from our paper, it is related to our paper in that this study also consider time and energy consumption of wearable device.

The role of smartphone as a bridge between wearable devices and outside or providing computing resources to wearable devices is commonly observed in many recent research works on wearable devices. In [24], a platform for energy harvesting in smart shoes is proposed. Smart shoes transmits sensor data to the smart phone. In [25], a sensing scheme of human activity is proposed for a smart glass and a smart watch. The two devices generate various raw sensor data and transmit them to the external cloud via smartphone, in which the type of activity is estimated by using the sensor data collected. This work focuses on the side of cloud. In [26], a scheme to track the maneuver of steering wheel is proposed to be used for a driver wearing a smart watch. The scheme recognizes a specific pattern of steering wheel so that it prevents a car accident or notifies the driver safety warnings. The communication link between smart phone and wearable device is the common basic component in all these works. Our scheme can be used to enhance the energy efficiency of the wearable devices in these scenarios.

Our paper is novel in that we apply data bundling to the Bluetooth connection between wearable device and smartphone