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Smartphone-assisted energy efficient data communication for wearable devices

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ABSTRACT

In dynamically changing network environments, no single data communication approaches for wearable devices are guaranteed to yield the best performance-cost ratio. To illustrate how different approaches perform in different environments, we conduct a theoretical analysis to four basic approaches that rely on either Wi-Fi, or smartphone-tethered cellular network, or both, to transmit data on wearable devices. In order to achieve energy efficient data communication on wearable devices (and associated smartphones), we propose a Lyapunov based on-line approach designation mechanism that dynamically chooses an appropriate data communication approach based on data transmission queue, estimated network conditions and the device moving speed. Due to the property of Lyapunov optimization framework, the proposed mechanism is able to minimize the power consumption of data communication for wearable devices (and associated smartphones) while meeting the delay time constraint. Moreover, it requires no prior knowledge of future network conditions and data request arrivals. Our trace-driven simulations demonstrate that our on-line designation mechanism delivers very close performance to the mechanism that can foresee the future, leaving very little space for further improvement.

1. Introduction

Recently, the emerging wearable devices, such as Google Glass and Apple Watch, reveal great potentials to bring up another heated wave of technological enthusiasm. Their portability and hands-free interaction with humans will fundamentally change how the physical world is augmented by the seamless integration with the virtual world. Indeed, wearable devices are now fulfilling the vision of Internet of Things [1–3].

Though blessed with such vision, wearable devices will inevitably be faced with the issue of limited battery life, due to their inherent small form factor and the slow progress in battery technology. This generation of wearable devices are usually not equipped with cellular interface, and thus require being connected with smartphones via Bluetooth or other means of communications in order to be fully functional, such as making phone calls and sending/receiving SMS. Such continuous connection requirement further worsens the battery life on wearable devices.

One effective way to prolong the battery life on wearable devices is to improve the energy efficiency of their data communication [4]. Different types of network interface for data communication impose different power consumption. Normally, wearable devices can connect to Wi-Fi Access Points (AP) via their built-in Wi-Fi interface, or cellular stations via Bluetooth-tethering by their associated smartphones. Wi-Fi is generally more efficient than other network interfaces in terms of power consumption per unit speed [5]. However, blindly minimizing the energy consumption on wearable devices (i.e., using Wi-Fi) may lead to unexpectedly long delay in response, since Wi-Fi is not always available or stable. On the other hand, cellular network has a much wider coverage than Wi-Fi. However, relying on cellular network can greatly accelerate the battery draining on smartphones.

In this paper, we focus on the problem of energy-efficient data communication between wearable devices, smartphones, Wi-Fi APs and cellular stations. The goal is to jointly minimize the energy consumption of data communication on both smartphones and wearable devices subject to a delay time constraint. Yet, there exist two major challenges to solve the problem. First, the solution must be easily applied to most off-the-shelf platforms, as nowadays wearable devices and smartphones may run on different operating systems. The proposed solution should work irrespective of the operating systems running on the devices. Second, the solution must perform equally well in both static and mobile environments in terms of energy efficiency. In mobile environments, Wi-Fi AP availability and quality change constantly due to user mobility [6], resulting in significantly different performance. Since it is fundamentally difficult to predict the variation in Wi-Fi AP avail-

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ability and quality, the solution must avoid using prediction-based techniques.

Contributions. *To have cross-platform support*, we investigate four approaches that users can actually adopt in practice to enable data communication for both devices. These approaches do not require system-level code modification, or complicated coordination between both devices. However, our theoretical analysis shows that they deliver different performance in achieved bandwidth and power consumption across a variety of environments. *To perform equally well in static and mobile environments*, we propose a Lyapunov-based on-line designation mechanism to determine which approach to adopt so as to minimize energy consumption while ensuring quality of service (e.g., delay time). Due to the property of Lyapunov optimization framework, the proposed mechanism does not require any prior knowledge of future network conditions and data request arrivals. It uses smartphones to monitor environment information (e.g., network bandwidth and density), as well as data transmission queue to make energy efficient decisions.

To evaluate the performance of our on-line designation mechanism, we conduct extensive trace-driven simulations. To do so, we collect two types of real-world traces, user request traces and network availability and quality traces, both of which have a significant impact on the performance of our mechanism. Using these real-world traces makes it possible to compare our mechanism with others in a controlled environment, yet being able to generate convincing results. We compare our mechanism against static mechanisms that only adopt one fixed approach, as well as other dynamic mechanisms that adopt approaches based on different rules. Simulation results show that our mechanism delivers consistently better performance than static mechanisms and other dynamic mechanisms. We also demonstrate that the performance of our mechanism is very close to the ideal mechanism that can foresee the future, leaving very little space for further improvement.

The rest of the paper is organized as follows. We present the problem formulation in Section 2. Followed is the pool of practical approaches in Section 3 and the on-line approach designation mechanism in Section 4. We evaluate our proposed mechanism and present the trace-driven simulation results in Section 5. Related work can be found in Section 6. Finally, we conclude this paper in Section 7.

2. Problem formulation

2.1. System model

We consider a new mobile computing model, where wearable devices, smartphones, Wi-Fi APs and cellular stations are actively involved in data transmissions. The smartphone is equipped with cellular, Wi-Fi and Bluetooth interfaces, and can decide whether to enable Bluetooth tethering to provide network access to the associated wearable device. The wearable device is only equipped with Wi-Fi and Bluetooth, and will first attempt to establish network connections via Bluetooth tethering on the smartphone, and if failed, will repeat the attempt via Wi-Fi. Now, we make several reasonable assumptions as follows. Cellular stations are deployed in such a way that it provides its users with constantly stable access to Internet, while Wi-Fi APs only provide intermittent network connections with varying quality. The smartphone maintains a constant connection with the wearable device via Bluetooth, since it is necessary for the latter to take over basic functions available on the former, such as making phone calls and sending text messages. Both devices are also assumed to keep Wi-Fi turned on, and Wi-Fi is in Power Saving Mode (PSM) when not used to save energy. Fig. 1 gives an overview of the established model.

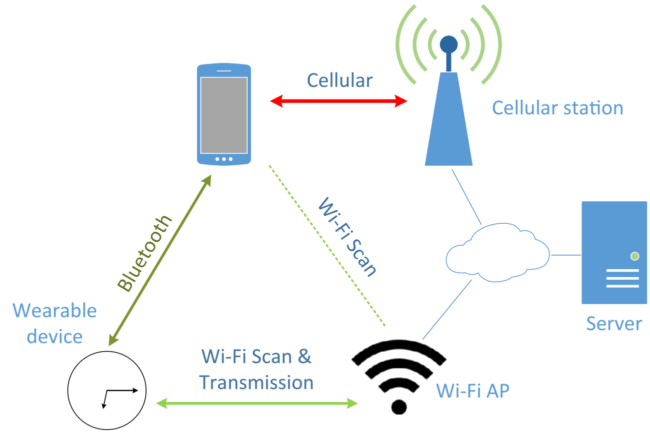

Fig. 1. Data communication model.

Based on the model, we focus on the problem of energy efficient data communication among wearable device, smartphone, APs and cellular stations. The wearable device needs to transmit data to and download data from remote servers. It can either tether the smartphone or connect to an AP for data communication between itself and remote servers. To solve the problem, we need to design efficient methods to coordinate the communication among devices according to available wireless resources around the wearable device, as shown in Fig. 1. Specifically, we study the problem of *minimizing the overall energy consumption of both the wearable device and the smartphone subject to some delay time requirement*.

A theoretical optimal solution would be easy to obtain for this problem, if we could foresee all the relevant information in the future, such as paths that users will take, request arrival time, etc. However, such assumption is not realistic in practice, as users move randomly in unknown environments, and request Internet connections randomly. Although prediction techniques may be applied to estimate future information, they are expensive yet unable to guarantee accurate estimates for all predictions. Moreover, solutions generated under erroneous estimates would incur even more energy consumption than those without any predictions.

2.2. Approach designation mechanism overview

To make this problem more tractable, we investigate a pool of practical approaches for data communication, from which we dynamically designate one that achieves good energy efficiency while satisfying the delay time requirement. These practical approaches vary in different performance metrics, such as power consumption for different devices and incurred delay time. Now, the new problem becomes *how to designate approaches to minimize the overall energy consumption subject to some delay time requirements*. Note that, adopting a limited number of practical approaches shrinks the set of feasible solutions, thus possibly risking not finding any solutions that are theoretically optimal to the original problem. Nevertheless, these practical approaches represent a set of feasible solutions that we can easily apply to most off-the-shelf platforms, and thus fit better with the real-world use case.

Like the original problem, an optimal solution to the new problem also requires foreseeing the future. In other words, all inputs should be given in advance so as to optimally designate approaches, which, again, is not realistic in practice. This leads us to propose an on-line approach designation mechanism that makes decisions only based on historical and present environment information, such as AP quality and user moving speed. Meanwhile, this mechanism should not assume any probability distributions of AP

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