Pervasive and Mobile Computing 30 (2016) 45–57

Contents lists available at ScienceDirect

Pervasive and Mobile Computing

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

Enhancing WiFi-fingerprinting accuracy using RSS calibration in dual-band environments

Taehwa Choi, Yohan Chon, Yungeun Kim, Dongwon Kim, Hojung Cha *

Yonsei University, Seoul, Republic of Korea

A R T I C L E   I N F O

Article history:
Received 18 February 2015
Received in revised form 18 June 2015
Accepted 17 October 2015
Available online 26 October 2015

Keywords:
Indoor localization
Wi-Fi fingerprinting
Scan update delay
Speed estimation

A B S T R A C T

Wi-Fi radio signals are commonly used to localize mobile users indoors. The use of a dual-band channel (2.4 GHz and 5 GHz) in mobile devices, however, significantly affects the accuracy of localization, because scanning all the channels requires a relatively long delay of approximately 5 seconds. During this scan time, a user may move tens of meters, depending on his or her walking speed. In this paper, we propose the self-calibration of Wi-Fi signals in a dual-band channel to solve the received signal strength (RSS) delay problem in Wi-Fi-based indoor localization. We first investigate the causes of RSS delay by analyzing Wi-Fi driver implementation and observing users' walking behaviors. The proposed system comprises four components: a delay detector, a speed calculator, a search window manager, and a window selector. The delay detector estimates the delay in Wi-Fi scanning at each access point. The speed calculator estimates a user's walking speed using an accelerometer. The search window manager quantifies the size of the reference fingerprints from the radio map based on the update delay and movement speed. The window selector revises the signals using the RSS compensation model. The experiment results in two buildings show that the proposed system greatly improves the accuracy of indoor localization.

1. Introduction

Indoor positioning techniques have actively been studied using radio signals, such as Wi-Fi, ZigBee, Bluetooth, and 3G/LTE networks. In particular, the IEEE 802.11 Wi-Fi technology is commonly used for indoor positioning because of its high popularity and penetration rate [1,2]. Recently, commercial mobile devices have begun to support dual-band radio frequencies (i.e., 2.4 and 5 GHz), which provide a wider range of available access points (APs) for indoor localization. However, AP scanning in a dual-band environment requires prolonged scan delays of an additional 32 channels in 5 GHz [3,4]. We term this issue the received signal strength (RSS) delay problem. In fact, the scan time of the APs in the low band is different from that in the high band, and the RSS packet of the APs in the low band is received earlier than that in the high band [3,4]. This phenomenon means that a single fingerprint consists of signal strengths of APs measured at different locations when a user is moving.

The RSS delay problem is a critical issue in indoor localization because the integrity of RSS value plays an important role in calculating location. By the time the scanned result is transmitted for calculating the location, some of the RSS data is already outdated due to the scan time. For example, the RSS of AP A is received at location X, but the RSS of AP B is actually scanned at Y, a different location. This scan delay in RSS has a direct impact on the accuracy of device positioning because the

* Corresponding author. Tel.: +82 2 2123 5711; fax: +82 2 365 2579.
E-mail address: hjcha@yonsei.ac.kr (H. Cha).

http://dx.doi.org/10.1016/j.pmcj.2015.10.017

Table 1
Scan time of mobile device.

Device	Platform	Supported band	Wi-Fi chipset	Average scan time (s)
Galaxy S4	Android	Dual band	Broadcom BCM4335	3.39
Galaxy Note 3	Android	Dual band	Broadcom BCM4339	3.51
Samsung T231	Android	Dual band	Marvell 88W997S	4.29
Samsung G350E	Android	2.4 GHz	Broadcom BCM4343S	1.12
Samsung Galaxy U M130L	Android	2.4 GHz	Qualcomm MSM6290	1.03
iPad 2	iOS	Dual band	Broadcom BCM43291	3.51
SM-W750V	Windows mobile	Dual band	Qualcomm WCN3680	4.43
RD-PQ	Tizen	Dual band	Broadcom BCM4334	3.59

error significantly increases as the user moves, especially when the user is moving quickly. The delay problem is inherently caused by the use of dual-band in WiFi environments, thus the problem exists in all types of mobile systems such as Android, iOS, Windows mobile, Tizen, etc. In order to deal with the RSS delay problem, an adequate scheme is therefore required for Wi-Fi-based indoor localization.

In this paper, we propose a self-calibration scheme that addresses the RSS delay problem in indoor localization. We investigate the fundamental causes of the RSS delay problem, and we subsequently design a system to handle the problems by analyzing Wi-Fi driver implementation and the characteristics of user movement. The proposed system comprises four components: a speed calculator, a delay detector, a search window manager, and a window selector. The system first estimates the initial position of a user using Wi-Fi fingerprints. The speed calculator estimates a user's walking speed using an accelerometer [5,6]. The delay detector then estimates the updated delays of each AP in the scanned fingerprints. The search window manager uses the updated delay data and the movement speed to determine the size of the search window in the radio map. Finally, the window selector revises the RSS using the selected RSS in the radio map. After self-calibration is completed for all the APs, the system estimates the location of the device. The main contribution of our work is to solve the RSS delay problem in dual-band environments, which has not been addressed in the literature.

This paper is organized as follows. In Section 2, we describe the RSS delay problem by explaining the mechanism of Wi-Fi scanning and the scan time in both single- and dual-band environments. Section 3 provides a description of the system we developed to resolve the RSS delay problem in indoor localization. In Section 4, we evaluate our approach with experiments at two different sites and discuss the performance results. Section 5 offers a discussion of related work, and Section 6 concludes the paper.

2. Preliminary study

In this section, we describe the scanning mechanism of the IEEE 802.11 Wi-Fi technology and address the following questions:

- How long is the scan time delay in a dual-band environment?
- What is the main factor of this delay?
- How much error is caused by the RSS delay in indoor localization?

2.1. Wi-Fi scan delays in a dual-band environment

To clarify the RSS delay factor, we first explain the Wi-Fi scan mechanism. The IEEE 802.11 standards define 14 channels from 2.412 GHz up to 2.484 GHz, but Channel 14 (2.484 GHz) is not used due to the overlap with an existing frequency. The 5 GHz band has noncontiguous channels assigned between 5.180 and 5.825 GHz in the frequency spectrum. The channel bandwidth is 20 MHz, but two channels can be combined to form a channel with a 40-MHz bandwidth [3,4]. Fig. 1, for example, shows that 32 channels are scanned between Channel 1 and Channel 161 on a Samsung Galaxy 4 smartphone.

In a dual-band environment, channel scanning requires more time than it does in a single-band environment. This is further illustrated in Table 1. Our measurement shows that the scan time in a dual-band environment is about 3.3 s longer than in a single-band environment. The difference in scan time between devices is due to varying configurations of channel scanning in firmware implemented by chip vendors. Note that such delay in scan exists in all types of mobile platform including Android, iOS, Windows mobile, and Tizen. In addition, the scan time may increase according to various factors, such as the number of neighboring APs, the number of overlapping channels of close APs, the delays caused by contentions, and so on [7].