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Unsupervised context detection using wireless signals

Dinh Phung [a,*], Brett Adams [a], Svetha Venkatesh [a], Mohan Kumar [b]

[a] Department of Computing, Curtin University of Technology, GPO Box U1987, Perth, WA 6845, Australia

[b] Department of Computer Science and Engineering, The University of Texas, Box 19015, Arlington, TX 76019, USA

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ABSTRACT

The sensing context plays an important role in many pervasive and mobile computing applications. Continuing from previous work [D. Phung, B. Adams, S. Venkatesh, Computable social patterns from sparse sensor data, in: Proceedings of First International Workshop on Location Web, World Wide Web Conference (WWW), New York, NY, USA, 2008, ACM 69–72.], we present an unsupervised framework for extracting user context in indoor environments with existing wireless infrastructures. Our novel approach casts context detection into an incremental, unsupervised clustering setting. Using WiFi observations consisting of access point identification and signal strengths freely available in office or public spaces, we adapt a density-based clustering technique to recover basic forms of user contexts that include user motion state and significant places the user visits from time to time. High-level user context, termed rhythms, comprising sequences of significant places are derived from the above low-level context by employing probabilistic clustering techniques, latent Dirichlet allocation and its n-gram temporal extension. These user contexts can enable a wide range of context-ware application services. Experimental results with real data in comparison with existing methods are presented to validate the proposed approach. Our motion classification algorithm operates in real-time, and achieves a 10% improvement over an existing method; significant locations are detected with over 90% accuracy and near perfect cluster purity. Richer indoor context and meaningful rhythms, such as typical daily routines or meeting patterns, are also inferred automatically from collected raw WiFi signals.

1. Introduction

The proliferation of small computing mobile devices, such as smartphones, iPods, eEPCs, ultraportable computers has brought new opportunities and challenges for ubiquitous computing [1]. On one hand, a more prevalent trend is that these devices are rapidly equipped with sensing capabilities: GPS receivers, WiFi, Bluetooth transceivers, and many more. On the other hand, mobile computing has increasingly broadened computing perspective in everyday user's context, being, at least, either situational or interactional. Three useful contexts are motion state, location and movement patterns over time and space. Location often correlates with certain activities or roles [2], and aspects of the user's physical states, such as motion, are also indicative of activity and the user's affordances (e.g. interruptibility). This information can drive applications at many levels, from automated battery management to assistive systems (e.g., for the visually impaired). Device convergence has made available a number of sensing and communication technologies, including Bluetooth, WiFi and GPS, for extracting these elements of context. Our early work has considered the problem of context extraction in an outdoor setting using

* Corresponding author.
E-mail addresses: d.phung@curtin.edu.au (D. Phung), b.adams@curtin.edu.au (B. Adams), s.venkatesh@curtin.edu.au (S. Venkatesh), mkumar@uta.edu (M. Kumar).

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GPS [3,4]. In this paper, we design, develop and evaluate novel, high accuracy mechanisms for extracting user context in indoor environments. User motion level and significant locations, defined as places where a user spends time, are extracted from raw WiFi signals in a timely, unsupervised, and accurate manner, in existing wireless network infrastructures. We further provide methods on how this fundamental information can be used to discover such higher-level contexts as the user's daily routines or *rhythms* in an unsupervised setting.

Much work has been done in the use of GPS to derive representations of significant locations in outdoor situations. There has also been significant activity in localization from signatures that penetrate or originate indoors, such as WiFi, GSM, and Bluetooth. Work aimed at characterizing the physical state of a user has tended to make use of sensors that are not as readily available as ambient radio signatures, such as thermometers, galvanic sensors and accelerometers. A brief review of relevant work is provided in Section 2. In [5] location and orientation estimations based on Bayesian filtering of received signal strength (RSS) justifies the use of WiFi signals for extracting location context. The Locadio positioning system of [6] uses WiFi signals to infer whether or not a user is moving based on the variance of signal of the strongest WiFi access point (WAP) within a short window, achieving an accuracy of 87% after a post-processing step with a 2-stage hidden Markov model (HMM). Often, the noisy, sparse nature of WiFi signatures renders models based on a simple Gaussian assumption to become problematic in this case. An additional shortcoming of Locadio is the requirement for training. Moreover, in the original setting of Locadio [6], prediction is made with a latency of 20 s, which disqualifies the approach from real-time applications, such as navigation assistance for the visually impaired.

Build upon our preliminary work in [7], instead of viewing motion state detection as a supervised classification problem, we cast it as an unsupervised and incremental clustering problem. A window of consecutive WiFi signatures observed from the same location, when the user is still, are likely to be similar, and thus is more likely to form a dense cluster as opposed to those when the user is moving. Similarly, if WiFi signals observed during a user's daily life are collated, locations where the user spends time repeatedly, for example at their desk at work, will also emerge from a clustering process. We define a measure of distance between two WiFi observations appropriate to their characteristics, notably allowing for missing data from the vectors of WAP signal strength. We use a density-based technique, DBSCAN [8] and its incremental version [9], to recover the user's motion level and significant locations. Use of incremental DBSCAN allows for motion level classification with latency under 2s, which can potentially be suitable for many real-time applications. We conduct comprehensive experiments to compare the Locadio method with our density-based approach for detecting the user state. We achieve up to 95% accuracy, an improvement of 10% over Locadio's approach in [6], suggesting that our method is more robust despite noisy and incomplete WiFi data. We experiment with detection of significant locations, using pre-filtering to remove observations when the user is moving, resulting in an accuracy of above 91% with almost perfect clustering purity (98%).

To further motivate the extraction of motion state and significant locations, we also present a technique for discovering user indoor movement behaviors over time, termed *rhythms*. It has been shown that travel episodes often correspond to hidden agendas or 'social projects' [10], and we posit that a similar situation occurs at finer resolutions, say, within the office. Discovery of these rhythms offers potentially rich information about user intent and activity. We adapt a probabilistic graphical model, Latent Dirichlet Allocation (LDA) [11], for this task. LDA is an unsupervised probabilistic clustering technique used to discover latent topics from bags of words in text by finding co-occurrences of words in documents. Here, significant locations and their observed times are extracted and are mapped to words. These are then collated over a day and become analogous to a document. The latent topics discovered by LDA in this way are interpreted as user rhythms. We experimented with the discovery of rhythms for a user over the course of a one month period.[1] While interpretable and meaningful office patterns can be clustered, LDA does not truly model the temporal information between landmarks due to its strict 'bag-of-word' assumption. To this end, we extend our previous work using LDA in [7] to employ an n-gram extension of LDA known as n-gram topic model (NLDA) [12] and show that richer trajectory patterns can be automatically discovered such as typical daily routines or research meeting patterns. In all cases, the results from the hidden Markov model are also presented as a baseline performance for comparison.

The first novel contributions in this paper, which were earlier developed in [7], are two-fold: the development of unsupervised and incremental algorithms for high accuracy motion; and the real-time detection of significant places visited using WiFi signals. *In addition to* [7], *a significant novel contribution unique to this paper is the extraction of rhythms using rich Bayesian probabilistic models that explicitly capture temporal and spatial information in a sensor agnostic manner in an indoor setting*. The ability to infer a mobile user's context is a vital and foundational component for a broad array of pervasive computing applications. Our investigations enable both richer representation and more accurate extractions of different aspects of context, and hence the outcomes of the research work presented in this paper can potentially be valuable to various applications. The two-fold contributions can serve as a basis for both annotation and prediction at a number of levels of the services stack. Importantly, the absence of a requirement for calibration and use of existing infrastructure makes for a low barrier to deployment. The applications include, context-sensitive device resource and interface management, semi-automatic calendaring, personal life logs and collaboration tools, personalized push-information such as advertising, and navigation assistance for the visually impaired. In a shared context, this information can aid market research, surveillance and urban planning.

[1] It is worth noting from the perspective of assistive systems that the incidence of strict routines is even higher among the visually impaired, presumably due in part to the desire to decrease the number of variables that might induce danger or inconvenience for themselves or others, making rhythms more compelling in this application domain.