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# Roadmap to Anticipatory Mobile Computing

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**Abstract.** Growing pervasiveness and personalisation of mobile computing devices, have raised the need for their autonomous, yet intelligent proactive actioning. Such a functioning encapsulated in the concept of anticipatory computing has been a subject of academic research for more than thirty years. Yet, before the recent advances in ubiquitous computing, anticipatory computing remained confined primarily to theoretical explorations. In this paper we discuss the basics of anticipatory mobile computing, a novel concept that builds upon mobile sensing, machine learning and the intrinsic ways mobile devices are nowadays used, in order to enable novel proactive and personalised applications.

**Keywords:** mobile computing, pervasive computing, anticipatory computing, wireless networks

**Pregled napovednega mobilnega računanja**

Naraščajoča prodornost in personalizacija mobilnih naprav sta povečali potrebo po njihovem avtonomnem, inteligentnem in proaktivnem delovanju. Takšno delovanje, v okviru koncepta napovednega računanja, je predmet akademskih raziskav že več kot trideset let. Vendar je bilo še pred zadnjimi napredki na področju vseprisotnega računanja napovedno računanje predmet teoretičnih raziskav. V tem članku obravnavamo osnove napovednega mobilnega računanja, novega koncepta, ki združuje mobilno zaznavanje, strojno učenje in različne načine današnje proaktivne in personalizirane rabe mobilnih naprav.

## 1 Introduction

A pedestrian with a mobile phone walks around a city utilising WiFi access points (APs) in the most efficient way possible – the phone proactively allocates resources as it predicts by which AP the user will pass next. The phone also predicts the length of stay at a certain AP, so that data-heavy tasks, such as large photo uploads, are not attempted at times when the user is just intermittently connected. In another example, a smart wristband keeps track of a user's heart rate. It predicts that the user is in risk of being highly stressed out. The system combines a user's smartphone that accesses the user's calendar and examines tasks scheduled for today. The phone then intelligently schedules tasks to alleviate the risk of high stress and suggests a new schedule to the user.

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These examples showcase the potential anticipatory computing has to improve our daily lives. In this position paper we introduce a concept of the anticipatory mobile system, examine recent advances in hardware and software that enable such a system, and present challenges and opportunities in this nascent field.

## 2 Anticipatory Mobile Computing

Anticipation – prediction of future states and events, and reasoning about how to act upon these predictions, is an inherent ability of intelligent beings. *Anticipatory computing* is a research area born from the efforts to bring artificial intelligence closer to nature, and incorporate anticipation into computing systems. An often quoted definition of the anticipatory system is provided by Rosen:

> *"A system containing a predictive model of itself and/or its environment, which allows it to change state at an instant in accord with the model's predictions pertaining to a later instant" [12].*

Two important prerequisites for a functional anticipatory system stem from the above definition. First, such a system needs to be capable of reasoning upon the past, present and future, predicted state of a model. Second, this model has to realistically describe the system and its environment – it has to be *context aware*.

Anticipatory reasoning, its formalisation and mathematical foundations have been developed over the last thirty years [1], [8]. Limited practical implementations have been delivered in the area of robotics [13], yet wider proliferation of anticipatory systems has been limited by the lack of powerful, context-aware computing devices.

Mobile pervasive devices have seen tremendous advances in recent decades. Equipped with an array of sensors and powerful processing hardware that can support sophisticated machine learning algorithms, devices such as smartphones, can build predictive models of the context. Based on these models, actionable decisions that impact the future state of the system and/or its environment can be made. Furthermore, tight integration with user's lifestyle ensures that these actionable decisions, delivered via mobile pervasive devices, are both relevant to the user, and communicated to the user when needed.

In Figure 1 we show a sketch of an anticipatory mobile computing system. The core building blocks include not only context sensing, state modelling and decision logic, but also a component that is in charge of efficient communication with the user. The existence of the human in the loop is a key property that distinguishes mobile pervasive systems from previous attempts to realise anticipatory computing systems.

## 3 Hardware and Software Enablers

Modern mobile computing devices are equipped with an array of sensors. Today's smartphones, such as Samsung Galaxy S5 host an accelerometer, barometer, gyroscope, GPS, light and proximity sensors, to name a few. A range of modalities that a phone can sense through these sensors increases its ability to recognise complex states of its user and the environment. Examples include the inference of the user's physical activity, gestures, emotion, and stress levels.

The set of the available sensors increases with every new generation of smartphones, yet increasing the number of modalities and more sophisticated data processing require substantial computing resources. A small form factor and a limited battery charge constrain smartphone designers when it comes to placing powerful CPUs and a large amount of memory on the devices. Low power consumption processing chips that explicitly target mobile devices are highly sought for; e.g one such chip manufacturer – ARM – has seen a 30% sales increase from March 2012 to March 2013.

Context inference and modelling are two of the most processing hungry aspects of an anticipatory mobile system. Machine learning algorithms are used to convert raw sensor readings from GPS, accelerometer and other sensors, into high level concepts. The steps included in the mobile sensing processing chain are *physical sensing*, *feature extraction*, and *modelling*. Feature extraction converts raw readings into a form suitable for modelling algorithms, and often include Fourier transforms, spectral processing, and similar. Modelling relies on machine learning algorithms to infer the relationship between high level concepts and the extracted features. In our recent survey paper on anticipatory mobile computing we present a breakdown of machine learning approaches used in the mobile sensing literature [9]

In a mobile computing ecosystem devices are seldom isolated. Situations where a number of smartphone users travel on the same train, a group of friends enjoys a dinner together, or geographically dispersed fans tweet about a release of a new film, are common. Internetworking has a strong impact on the mobile sensing practices as well. Instead of building models for a single individual and from a limited amount of sensed data, we can harness larger amounts of data from multiple users and increase the accuracy of our models. But not all data is useful, and we need to identify groups of users that behave in a similar manner and can share the developed models. Community similarity networks have been proposed by Lane et al. to connect mutually similar users and build common inference models for such users [5]. When it comes to anticipation, multiuser behaviour is interesting as modifications induced in one person's future can impact another one. For example, if an anticipatory mobile application senses that a user is about to commute via a road that is going to become congested, it might suggest a less congested alternative. If all other users also get the same suggestions the less congested road might not be less congested in a near future.

Finally, new hardware solutions, including wearable computing devices such as Google Glass [3], may truly bridge the gap between our physical context and the device. Novel hardware is also poised to solve some of the energy, processing, storage and communication issues. Qualcomm Consia, for example, aims to support on-chip contextual learning and prediction [14]. With a dedicated hardware preprocessing component Consia is bound to improve energy efficiency and responsiveness of mobile context sensing. On the software side, Google has released its activity recognition API for Android devices [2] drastically simplifying context-aware application development.

## 4 Opportunities and Challenges

The potential for anticipatory mobile computing applications is yet to be revealed as innovative applications hit the market. Here we present three possible avenues for research and development.

- **Personal Assistant Technology** Mobile devices are increasingly personal. Information about our email and SMS correspondence, online social networks contacts, planned events from our calendars, is readily available for mobile applications to use. Combined with physical sensor data can represent a basis for highly personalised models that can anticipate the user's future context. A personal

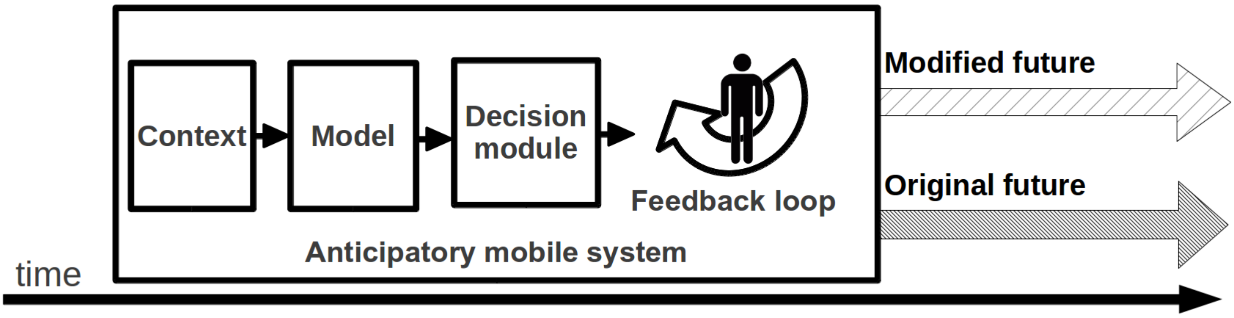


Figure 1. Anticipatory mobile systems predict context evolution and the impact their actions can have on the predicted context. The feedback loop consisting of a mobile and a human, enables the system to affect the future.

assistant application of tomorrow might help us organise our day in the most efficient way, even predict encounters we will have, and direct us in human-to-human interactions.

- **Healthcare and Wellbeing** Mobile sensing, both via smartphones and wearable devices such as Jawbone, is used to provide continuous monitoring of a user's health-state. On top of the health state information personalised therapies can be built, and preloaded on users' phones [4], [7], [15]. Yet, with anticipatory computing therapies can go a step further and adapt, so to drive the user's future health state. We term such applications anticipatory digital behaviour change interventions and refer the reader to a related overview publication [10].
- **Smart Cities** Today's cities are plagued with problems, including pollution, overpopulation, and crime. Still, cities are drivers of economy, and are forerunners of ubiquitous technology adoption. Anticipatory mobile computing systems can harness the pervasiveness of mobile devices in cities to deliver large-scale applications specifically tailored to solving the above problems. For example, sensor data from a large number of users can help estimate and alleviate traffic congestion. In addition, people-centric anticipatory mobile computing promises a radical advancement of the way we tackle social problems. Distributed *surveillance* [6], for example based on opportunistic sensing, can be harnessed for early detection of violent riots or terrorist acts. Moreover, through a feedback loop, citizens can be provided with a personalised advice of how to avoid harmful consequences, or organize into first-aid smart mobs [11].

Despite the significant commercial interest, evident through predictive applications such as MindMeld, Yahoo Aviate and Google Now, full-fledged anticipatory mobile computing applications are not yet available. Numerous challenges associated with such applications need to be resolved first. We briefly discuss two important challenges:

- **Resource efficiency** Mobile sensors, especially those on smartphones, were not designed for continuous sensing needed for building reliable models of context state evolution, and currently represent the most resource hungry part of these devices. Techniques, such as adaptive sampling and hierarchical ordering of sensing modalities according to their resource usage, are used to increase the efficiency of mobile sensing. Yet, with an ever increasing number of sensors on the mobile, the problem of the sensing efficiency is complicated further and remains far from solved.
- **Learning in different domains** Identifying the relationship between the sensor data and an event or a property of interest, and modelling the evolution of the relationship is just one aspect of anticipatory mobile computing where machine learning has to be applied. Conventional issues with machine learning such as the lack of labelled data for classifier training are observed in this domain. Another aspect, inferring the relationship between the user and the anticipatory system, such as between a person under anticipatory mobile digital behaviour intervention therapy and the application that delivers the therapy, imposes additional challenges. In this case, obtaining training data can be extremely difficult, e.g. getting information on how a person under a stress-management therapy reacts to a certain meeting schedule, and can negatively interfere with the system, e.g. changing the above person's meeting schedule can raise a stress level of the person. Further discussion on this topic can be found in [10].

## 5 Conclusion

In this paper we provide an introduction to the anticipatory mobile computing system, a concept in which the potential of modern mobile computing devices is harnessed to provide intelligent actionable decisions based on the past, present and predicted future state of the system and its environment. We emphasise the multimodal sensing and high processing capabilities of the today's mobile phones as the main enablers of the anticipatory mobile computing systems. Finally, we present possible avenues for practical applications and outline challenges related to resource efficiency and machine learning implementations that are yet to be overcome. This position paper serves as a brief intro to a complex but promising field. For a more thorough background on the topic we refer the reader to our survey paper [9].

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