

7

Conclusion

The GAMBAS middleware encompasses several subsystems covering an adaptive data acquisition, interoperable data modeling and distributed processing, automated privacy preservation as well as associated user interfaces. As described in Chapter 3, Chapter 4 and Chapter 5, these subsystems can be further split into concepts, frameworks, mechanisms and protocols. In the following, we briefly revisit their functions and highlight their technical innovations.

Given that the GAMBAS middleware aims at supporting behavior-driven services, the data acquisition framework is clearly one of the fundamental building blocks of the GAMBAS middleware. Conceptually, the framework is responsible for context recognition on personal mobile devices including smart phones, PDAs and laptops. The framework supports various platforms including Android, Windows and Linux. It follows a multi-stage approach, which enables the development of context recognition applications from generic components that can be executed in an energy-efficient manner. To do this, the data acquisition framework leverages a component abstraction to foster genericity and a state machine abstraction to enable the energy-efficient execution of complex context recognition logic. Both these subsystems have been extensively used in development of various applications and technical demonstrations of GAMBAS. Some of the examples include the recognition of the user's context during a multimodal trip in order to support micro-navigation or the detection of noise and crowd levels to improve the user experience while traveling.

In order to make the acquired data usable by different applications, the GAMBAS middleware introduces interoperable data representations that follow the linked open data principles and are based on semantic web technologies. The GAMBAS ontology not only enables different applications to leverage the same data, but it is also used internally by the middleware,

for example, to model users and privacy policies. It is also noteworthy to mention that the ontology, that is accompanying the GAMBAS middleware, is not trying to reinvent the necessary concepts. Instead, it integrates a large number of ontologies that are already actively used. This increases the compatibility and simplifies the application development. On top of the interoperable data representations, the GAMBAS middleware introduces a dynamic data processing system that features a semantic-based auto-discovery powered by an associated linked open-data infrastructure. This infrastructure leverages a dynamic data registry to make data available across arbitrary applications, and it features data storages that can be queried locally and remotely. Using the efficient implementation of semantic data storages, it is possible to use standard query languages for semantic data even on resource-poor mobile devices while maintaining a query performance that is suitable for complex applications such as the mobile navigation application described in Chapter 6. Using specifically designed language extensions such as CQELS, the GAMBAS middleware not only supports queries on static data, but instead, it also allows evaluation of continuous queries over dynamic data streams. However, since this requires a higher amount of processing power, this support is not integrated directly into mobile devices. Instead, the GAMBAS middleware uses a distributed query processing architecture that offloads the effort to more powerful systems.

As a result of the automated acquisition of context information and the distributed processing of context information enabled by the GAMBAS middleware, security and privacy are becoming key issues that must be considered. For this reason, the GAMBAS middleware encompasses mechanisms and protocols to automate the preservation of the user's privacy as far as possible. In this context, it is worth pointing out that the GAMBAS privacy preservation framework goes well beyond encrypted communication by managing the access to the user's data on the basis of the user's privacy policy. To do so, it integrates with all other system components including the data acquisition framework, dynamic data registry and the semantic data storages running on devices of the user's and services deployed on the Internet. To implement access control on top of authenticated communication, the privacy framework allows users to automatically bootstrap the required encryption keys through popular online services such as Facebook. This not only minimizes the friction of secure data sharing, but it also enables secure peer-based (i.e. server-less) sharing of data between user devices without any manual configuration. Similarly, to minimize the user effort for setting up privacy policies, their generation can be (partially) automated through these services

as well. Towards this end, the privacy framework encompasses a policy generator that interprets the sharing behavior of a user to derive a suitable policy generation.

Together, these concepts, frameworks, protocols and mechanisms provide a generic structure that simplifies the development of behavior-driven services. This has been successfully demonstrated by the large number of applications and services that have been built using the GAMBAS middleware during its development. The applications implement several innovative features that are based on the user's behavior. This includes the automated capturing of user-specific information (e.g. intended trip destinations, noise exposure, etc.) as well as the privacy-preserving sharing of derived information (e.g. crowd levels, high-demanded routes, noise pollution in the city, etc.). The resulting data can be made available to service operators such as the bus network operators from EMT Madrid, which allows them to optimize their services, e.g. by dispatching more buses when high-demanded routes or destinations are detected.

Over the course of the project, the GAMBAS middleware has been made publicly available to third-party developers. The full source code of GAMBAS is available via a public Maven repository that can be reached through the project website. The source distribution includes tutorials and example applications to showcase and demonstrate the use of the middleware to simplify the development of applications leveraging behavior-driven services. In addition, the distribution also includes binaries in the form of a software development kit that is packaged to support application development on a broad range of different platforms.

From an academic perspective, the development of the GAMBAS middleware has resulted in a significant amount of research contributions beyond the state of the art. During the 3-year-long development of the GAMBAS middleware and its applications, the members of the GAMBAS consortium published specific concepts, algorithms and evaluations in more than 25 papers and articles in academic conferences and journals with high visibility. Furthermore, the consortium organized 5 different stakeholder workshops that shaped the design of the middleware significantly. Finally, the consortium demonstrated the GAMBAS technology and its applications at 3 different industrial events in order to disseminate the research beyond the academic sector.

In addition to publications, the availability of the GAMBAS middleware has resulted in a considerable pickup of the underlying implementations and

concepts through other research projects. For example, the SIMON Project¹ has reused most of the mobility-related services to implement a mobile application that provides mobility support for disabled and elderly persons in 4 major European cities. The SmartKYE Project² has reused the highly configurable component-based approach to data acquisition and processing provided by the data acquisition framework of the GAMBAS middleware in their energy-management infrastructure. Finally, the BESOS Project³ has reused concepts from the privacy framework and the SmartAction Project⁴ has reused GAMBAS for a joint IOT-middleware demonstration.

Given the current computing landscape with mostly centralized IoT infrastructures, we hope that this book will further strengthen the pickup of the approaches, concepts and technology developed and validated by the GAMBAS middleware and its applications.

¹SIMON Project Homepage: <http://simon-project.eu/>

²SmartKye Project Homepage: <http://smartkye.eu/>

³BESOS Project Homepage: <http://besos-project.eu/>

⁴SmartAction Project Homepage: <http://www.smart-action.eu/>