INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Project-Team aces

Ambient Computing and Embedded Systems

Rennes - Bretagne-Atlantique

Theme : Distributed Systems and Services

Activity Report

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Table of contents

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2. Overall Objectives

2.1. Overall Objectives

Three key phenomena have been changing the nature of computing over the last few years. The first is the popularity of portable devices such as mobile telephones and Personal Digital Assistants (PDAs). Today, around 80% of the French adult population possess their own mobile phone and there is a large variety of smartphones on the market that integrate PDA functionality. The second phenomenon is the large number of embedded systems; these are everyday devices that have their own processor and memory. Estimates suggest that more than 98% of the world's processor's are in embedded systems [16], thus facilitating the deployment of a variety of information systems that control physical objects. The third phenomena is the increasing variety of wireless networks available for personal and embedded devices, e.g., Bluetooth, Wifi, GPRS, etc.

The combination of these three phenomena has permitted the emergence of context-aware person-centric applications and collaborative personal environments. These services complement a person's physical ability to interact with his environment. They are tailored to the needs, preferences and location of each person carrying a device, and are continually available. Services range from critical, e.g., remote health monitoring [19], to utility, e.g., navigational help, etc. to value-added, e.g., virtual museum guides, smart home, etc.

The domain of person-centric computing is known in research circles as *ambient computing* [24], and several significant research challenges remain. First, to facilitate mobility, ambient computing services should require minimal device manipulation by the device owner. It is crucial that the computing device operate as an extension of the person rather than as a tool. Second, there must be a way of modeling the physical environment so that applications can seamlessly import data from the environment and modify the environment when possible. Third, applications must be able to adapt to the rather limited storage and processing capabilities of mobile devices, as well as to variable and intermittent wireless network coverage.

The ACES (Ambient Computing and Embedded Systems) group is addressing research from three angles:

- *System Support for Continuous Ambient Service Delivery*. A user needs to be able to exploit ambient services as seamlessly as possible. In particular, he should be shielded from the effects of network breaks – something that can be quite common for wireless environments.
- *Programming Models for Ambient Computing*. We have looked at ways of modeling the physical environment in the virtual environment of programs in order to facilitate ambient application development. The goal is to be able to write programs that address and navigate through objects in the physical world as elegantly as a program traditionally manipulates a computer's main memory.
- *Support for Collaborative and Business Process in Information Systems*. This point relates to collaborative environments in general. One issue is *Privacy in ambient systems*; this is needed in order to ensure user-acceptability for services and to ensure that services operate legally. A second issue is *digital restrictions management* (DRM) that define and enforce usage controls on content exchanged between devices. These are important in ambient and personal computing settings for security in order to defend privacy, licensing and general economic interests. Notably, the TPM (Trusted Platform Module) can be used to help support DRM. Finally, Free and Open Source Software (F/OSS) is a movement that permits access to software source code, and, encompasses a software development paradigm that harnesses the efforts of a distributed community.

This document overviews our activities in more detail. The section *Scientific Foundations* gives some background to our work in person-centric computing. The section *Application Domains* describes the importance of our research agenda through the presentation of several applications, some of which are being developed in our group. The group's recent results are presented in the section *New Results*.

3. Scientific Foundations

3.1. Introduction

The following paragraphs give a quick overview of the scientific background of the ACES research activities. Ambient computing and embedded systems are the foundations of person-centric computing. Our group is concentrating on *efficient ambient service delivery* and *programming models*; these are two essential and complementary aspects of ambient computing.

The challenge for ambient and embedded computing is to seamlessly merge information from the physical and virtual worlds, so that programs can act upon and influence the physical world around them. The purpose of a programming model is to represent information as data, and to provide a computational framework for data processing.

The last direction is to examine support for collaborative and business processes in information systems. The departure point of work on a new theme was to consider security issues for ambient information systems.

3.2. System Support for Continuous Ambient Service Delivery

Mobile networks are becoming increasingly heterogeneous. Global coverage is now well provided by 2G and 2.5G cellular systems, and 3G networks (UTMS) are being deployed in some densely populated areas. Nonetheless, very high data rates (WiMax, WiFi ...) will not be available everywhere in the near future, so the delivery of large amounts of information to people on the move will remain limited and expensive. In this context, the main challenge is to provide services as seamlessly as possible.

3.2.1. Pico-cell Architecture

The past few years have witnessed the rise of the cellular networks. These communication systems were designed with a philosophy of *any-time any-where* service. Users wish to receive and place calls at any location and without delay, to move while talking without interrupting their conversations. This requires ubiquitous coverage, which in turn requires significant infrastructure. A modern cellular system is installed with hundreds of base stations, at a cost of hundreds of millions of euros, in order that a communication link is always available. Such any-time any-where service provision becomes increasingly expensive and suffers from low bandwidth. Covering wide areas with high radio bandwidth requires complex equalization, due to signal attenuation, multi-path fade, and shadowing effects. Sophisticated radio engineering will lead to improved bandwidth, coverage, and mobile access, but this will be expensive, in terms of both capabilities and cost.

In this context, the ACES project has studied an alternate design for wireless networks where intermittent but very high speed is provided to the network through *Pico-cells*. The latter consists of a set of access points (APs), *i.e.* antennas around of which are defined radio cells with limited range (about 100 meters). Those antennas are discontinuously spread on the network area, thus providing a *many-time many-where* service. Actually, the idea of coverage discontinuity brings two major advantages. First, as it implies the use of a fewer number of access points, the architecture deployment will be cheaper. Second, radio cells disjunction hypothesis simplifies the radio frequency band management and avoids interference problems.

Even if this model simplifies network deployment, the connectivity intermittence induces important challenges in order to avoid service disruption. Thus, terminals have to take advantage of the high bandwidth when it is available. For delay tolerant data, a terminal stores data as it passes under a cell. Hence, it may consume the buffered data even when it passes through regions of poor network coverage. Many projects have studied very specific cases where the cells deployment is uniform and data is sent from servers to terminals (down-link). One example of this type of system is studied by WINLAB (Wireless Information Network Laboratory). In this project, cells are equally spaced and the data delivery algorithm is tested in a network with one dimensional system *i.e.* high ways.

Our approach is based on a more general case in which cells are distributed according to the envisaged traffic and data can be exchanged in both directions down-link (from servers to terminals) and up-link (from terminals to servers). The main challenge is to provide system mechanisms and efficient services addressing the specific constraints of this architecture: discontinuous coverage, user unconstrained mobility, high user density. To cope with the discontinuous coverage of the network, we store data (with caching mechanisms) close to mobile people, just before data delivery. Thus, the placement policy of data within the architecture is conditioned by knowledge of people on the move. The goal here is to define a representation of person mobility in the network architecture, and to use this model for placing data using limited and customised flooding mechanisms.

Through this architecture model, we underline the analogy between heterogeneous mobile networks and multiprocessor architectures (for example the mobile device can be considered as a processor). This approach allows us to map and extend existing caching mechanisms, taking into account the specific constraints of a discontinuous mobile network.

3.2.2. System Suppport in future 4G networks

Interactive IPTV, evolving internet behavior, and more generally new data services (location information services for example) will strongly influence mobile usage. This requires to support high users density at low cost. During the last four years, our first goal was to increase network capacity by using discontinuous coverage combined with system mechanisms (data caching and data distribution). Memory in the network and terminals facilitates service delivery.

It is now possible to go further. The 4G infrastructure operator will mix several technologies: large umbrella cells (3G, Wimax, DVB-based infrastructure), and numerous pico cells. In 4G context, the infrastructure will be much more distributed, and mobile terminals will have to collaborate with several entities in the network to perform service delivery. In other words, mobile terminals will become an active part of a complex information system distributed between several components in the architecture.

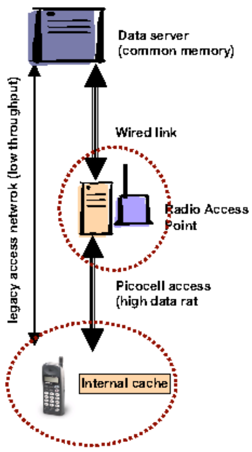

Figure 1. Pico-cell architecture model

We study system mechanisms to improve the terminal's integration in the network: ability to attach simultaneously several networks, capacity to opportunistically push data according to network conditions ...Terminal efficiency will depend on the number of technologies they can work with.

We have started to work on this problem by studying new possibilities offered by a large scale broadcast network coupled with a cellular network. We consider at first the future DVB-SH standard (satellite services to handheld devices) which is an hybrid (satellite/terrestrial) architecture. It is defined as a system for IP based media content and data delivery to handheld terminals, via satellite. Satellite transmission guarantees wide area coverage. Moreover, it is coupled with terrestrial gap fillers assuring service continuity in areas where the satellite signal cannot be received (built-up areas for example). In the context of our future works, a DVB-SH broadcast network is combined with a third generation network. Actually, this convergence will take benefit of 3G network characteristics, especially upload link, to enable added-value services and applications, which will be interactive and more personalized. For example, one could decide to deliver some classical 3G contents over DVB-SH path. This scenario occurs especially when contents or services suddenly become very popular, thus their transmission may take benefit of the large broadcasting capacities offered by a DVB network. The decision to switch a flow to the DVB-SH path could be based on the flow size and nature and on the number of subscribers. The design of dynamic flow insertion over the DVB-SH network involves multiple mechanisms and raises several open issues.

3.3. Programming Models

The goal of ambient computing is to seamlessly merge virtual and real environments. A real environment is composed of objects from the physical world, e.g., people, places, machines. A virtual environment is any information system, e.g., the Web. The integration of these environments must permit people and their information systems to implicitly interact with their surrounding environment.

Ambient computing applications are able to evaluate the state of the real world through sensing technologies. This information can include the position of a person (caught with a localization system like GPS), the weather (captured using specialized sensors), etc. Sensing technologies enable applications to automatically update digital information about events or entities in the physical world. Further, interfaces can be used to act on the physical world based on information processed in the digital environment. For example, the windows of a car can be automatically closed when it is raining.

This real-world and virtual-world integration must permit people to implicitly interact with their surrounding environment. This means that manual device manipulation must be minimal since this constrains person mobility. In any case, the relative small size of personal devices can make them awkward to manipulate. In the near future, interaction must be possible without people being aware of the presence of neighbouring processors.

3.3.1. Programming Context

Information systems require tools to *capture* data in its physical environment, and then to *interpret*, or process, this data. A context denotes all information that is pertinent to a person-centric application. There are three classes of context information:

- The *digital context* defines all parameters related to the hardware and software configuration of the device. Examples include the presence (or absence) of a network, the available bandwidth, the connected peripherals (printer, screen), storage capacity, CPU power, available executables, etc.
- The *personal context* defines all parameters related to the identity, preferences and location of the person who owns the device. This context is important for deciding the type of information that a personal device needs to acquire at any given moment.
- The *physical context* relates to the person's environment; this includes climatic condition, noise level, luminosity, as well as date and time.

All three forms of context are fundamental to person-centric computing. Consider for instance a virtual museum guide service that is offered via a PDA. Each visitor has his own PDA that permits him to receive and visualise information about surrounding artworks. In this application, the *pertinent* context of the person is made up of the artworks situated near the person, the artworks that interest him as well as the degree of specialisation of the information, i.e., if the person is an art expert, he will desire more detail than the occasional museum visitor.

There are two approaches to organising data in a real to virtual world mapping: a so-called *logical* approach and a *physical* approach. The logical approach is the traditional way, and involves storing all data relevant to the physical world on a service platform such as a centralised database. Context information is sent to a person in response to a request containing the person's location co-ordinates and preferences. In the example of the virtual museum guide, a person's device transmits its location to the server, which replies with descriptions of neighbouring artworks.

The main drawbacks of this approach are scalability and complexity. Scalability is a problem since we are evolving towards a world with billions of embedded devices; complexity is a problem since the majority of physical objects are unrelated, and no management body can cater for the integration of their data into a service platform. Further, the model of the physical world must be up to date, so the more dynamic a system is, the more updates are needed. The services platform quickly becomes a potential bottleneck if it must deliver services to all people.

The physical approach does not rely on a digital model of the physical world. The service is computed wherever the person is located. This is done by spreading data onto the devices in the physical environment; there are a sufficient number of embedded systems with wireless transceivers around to support this approach. Each device manages and stores the data of its associated object. In this way, data are physically linked to objects, and there is no need to update a positional database when physical objects move since the data *physically* moves with them.

With the physical approach, computations are done on the personal and available embedded devices. Devices interact when they are within communication range. The interactions constitute delivery of service to the person. Returning to the museum example, data is directly embedded in a painting's frame. When the visitor's guide meets (connects) to a painting's devices, it receives the information about the painting and displays it.

3.3.2. *Spatial Information Systems*

One of the major research efforts in ACES over the last few years has been the definition of the Spread programming model to cater for spacial context. The model is derived from the Linda [18] tuple-space model. Each information item is a *tuple*, which is a sequence of typed data items. For example, `<10, 'Peter', -3.14>` is a tuple where the first element is the integer 10, the second is the string '"Peter" and the third is the real value -3.14. Information is addressed using patterns that match one or a set of tuples present in the tuple-space. An example pattern that matches the previous tuple is `<int, 'Peter', float>`. The tuple-space model has the advantage of allowing devices that meet for the first time to exchange data since there is no notion of names or addresses.

Data items are not only addressed by their type, but also by the physical space in which they reside. The size of the space is determined by the strength of the radio signal of the device. The important difference between Spread and other tuple-space systems (e.g., Sun's JavaSpaces [17], IBM's T-Space [25]) is that when a program issues a matching request, only the tuples filling the *physical space* of the requesting program are tested for matching. Thus, though SIS (Spatial Information Systems) applications are highly distributed by nature, they only rely on localised communications; they do not require access to a global communication infrastructure. Figure 2 shows an example of a physical tuple space, made of tuples arranged in the space and occupying different spaces.

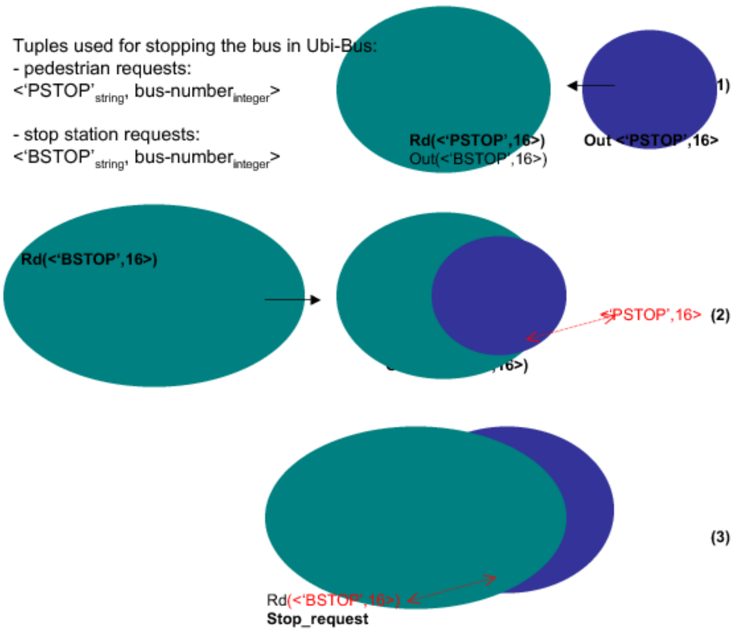

Figure 2. Physical Tuple Space

As an example of the power of this model, consider two of the applications that we have developed using it.

- *Ubi-bus* is a spatial information application whose role is to help blind and partially blind people use public transport. When taking a bus, a blind person uses his PDA to signal his intention to a device embedded in the bus stop; this device then contacts the bus on the person's behalf. This application illustrates how data is distributed over the objects of the physical world, and generally, how devices complement human means of communication.

- *Ubi-board* is a spatial information application designed for public electronic billboards. Travel hotspots like airports and major train stations have an international customer base, so bill-board announcements need to be made in several languages. In Ubi-bus, a billboard has an embedded device. When a person comes within communication range of the billboard, his device sends a request to the billboard asking it to print the message in the language of the person. In the case where several travellers are in proximity of the billboard, the board sends a translation of its information message to each person. The Ubi-board application illustrates personal context in use, i.e., the choice of natural language, and also how actions can be provoked in the physical world without explicit intervention by the person.

3.3.3. Coupled objects

Integrity checking is an important concern in many activities, both in the real world and in the information society. The basic purpose is to verify that a set of objects, parts, components, people remains the same along some activity or process, or remains consistent against a given property (such as a part count).

In the real world, it is a common step in logistic: objects to be transported are usually checked by the sender (for their conformance to the recipient expectation), and at arrival by the recipient. When a school get a group of children to a museum, people responsible for the children will regularly check that no one is missing. Yet another common example is to check for our personal belongings when leaving a place, to avoid lost. While important, these verification are tedious, vulnerable to human errors, and often forgotten.

Because of these vulnerabilities, problems arise: E-commerce clients sometimes receive incomplete packages, valuable and important objects (notebook computers, passports etc.) get lost in airports, planes, trains, hotels, etc. with sometimes dramatic consequences.

While there are very few automatic solutions to improve the situation in the real world, integrity checking in the computing world is a basic and widely used mechanism: magnetic and optical storage devices, network communications are all using checksums and error checking code to detect information corruption, to name a few.

The emergence of Ubiquitous computing and the rapid penetration of RFID devices enables similar integrity checking solutions to work for physical objects. We introduced the concept of *coupled object*, which offers simple yet powerful mechanisms to check and ensure integrity properties for set of physical objects.

Essentially, coupled ojects are a set of physical objects which defines a logical group. An important feature is that the group information is self contained on the objects which allow to verify group properties, such as completeness, only with the objects. Said it another way, the physical objects can be seen as fragments of a composite object. A trivial example could be a group made of a person, his jacket, his mobile phone, his passport and his cardholder.

The important feature of the concept are its distributed, autonmous and anonymous nature: it allows the design and implementation of pervasive security applications without any database tracking or centralized information system support. This is a significant advantage of this approach given the strong privacy issues that affect pervasive computing.

3.4. Collaborative Computing Processes

Today's systems have entered the era of community computing – the antithesis of personal computing. While people do possess their own handheld and personal computers, they indelibly rely on the community of computers and users for content, code, and services. Users also contribute resources – this phenomenon underlying the open source movement [22], utility computing, peer-to-peer computing, B2C, B2B, etc. Nonetheless, each user is constrained in his use of content and services by community rules, these being expressed through licensing and IP contracts, the Law (e.g., Sarbanes-Oxley [23], Basle II) or organizational rules. Thus, systems built today must be aware of digital restrictions management and support organizational requirements.

Community computing devices do not simply run applications – they participate in *processes*. A process is a goal-directed, inter-related set of activities. An example of a process is the operation of an on-line boutique service. The activities of this process include Web server maintenance, customer lists management, catalogue production, payment, etc. One challenge for process managers is to coordinate activities; for instance, information from the catalogue activity must be fed to the Web maintenance activity, feedback from the payment activity is needed for customer management. In effect, process efficiency depends on facilitating information flows between activities. A second important aspect of processes is the presence of legal and organizational issues, e.g., privacy (for customer data retention), Sarbanes-Oxley for data archival, and intelligent attribution of tasks to people within the organization for the efficient running of the boutique.

The objective of the this activity is to study abstractions for *process programming models* and their implementation. The role of a process programming model is to express activities. These activities involve people, their devices, computers as well as environment (embedded) computing devices. Compared to standard programming languages, process languages need to express concepts like principals (for people, organizations, etc.), roles (for security and organizational tasks), rules for content protection and security, events (for activity coordination) and process metering (for performance, security, etc.). Much work has been done on modeling processes in business information systems (e.g., BPEL [15]), though these are heavily dependent on XML. We would like an approach that is closer to high-level programming languages so that we can harness safety and portability. The case study of our approach is Free and Open Source software (F/OSS) processes, as this has legal, social, economic implications, and is also a method in which we can conduct our own developments.

4. Software

4.1. Introduction

The research tasks conducted in the ACES project lead to the development of many softwares. These developments are mainly realized, or at least initialized within the framework of industrial collaborations, and so they are attached to the application domains covered by the project.

4.2. SmartMuseum User Device Software

The general objective of the SMARTMUSEUM project is developing solution and IT services for user interest dependent (profiled) access to digitalized cultural information that is relevant in particular physical location. Within this project ACES developed the User Device (UD) software that is the main interaction point to the system for the mobile user. The main objective of this software was to provide the user with relevant object information, either browsing it online through connecting to a URL (specified on the RFID tag or composed from museum URL) or just reading the basic object information from the RFID tag. Our application presents object information in most relevant and suitable for the user way (text, audio, video, voice synthesis, multilingual support), considering the limitations of the UD screen and time constraints of the user. It is also able to collect statistical information based on the user actions (time spent and feedback) for updating user profile.

The functionalities of this software have been demonstrated during two international workshops:

- SEMAPRO event at The Third International Conference on Advances in Semantic Processing (Malta, October 2009),
- Conference on Online Cultural Heritage and User Communities, workshop organized in cooperation with Fondazione Rinascimento Digitale (Florence, December 2009).

5. New Results

5.1. Introduction

The ACES project is currently very active in three main research activities

- Definition of continuous services for 3G/DVB networks
- System architectures for pervasive computing
- Information system processes

In the following we give the major research results we got from these activities.

5.2. Efficient switched services over a DVB-SH / 3G network

Participants: Azza Jedidi, Frédéric Weis [contact].

The architecture studied in the scope of this work is based on a unidirectional DVB-SH broadcast network, coupled with a third generation cellular network. DVB-SH provides users with a variety of services, which could be classified in several categories. It offers real-time applications. Examples are TV-like broadcasting, live broadcasting and notification, which consists in broadcast notifications sent according to the preferences of the user (notifying a football fan of the retransmission of his preferred team matches for instance) and games, like real-time quizzes or multiplayer online role-playing games, etc. It also provides applications to download. For large general audiences, data file purchase services are offered, either on a subscription basis, such as downloading every morning the electronic version of the user's newspaper, or on an impulsive purchase basis, like for films, books and audio CD purchase.

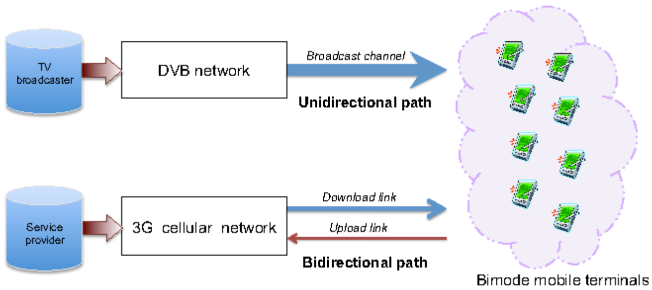

Figure 3. IP data switch

Besides, one of the main characteristics of the Internet world is its bidirectionality, permitting full interactivity to users. In this work, a DVB-SH broadcast network is combined with a third generation cellular network (3G network) to ensure this bidirectionality, as shown in Figure 3. Actually, this convergence takes benefit from 3G and DVB networks. 3G network characteristics, especially upload link, enable added-value services and applications that are interactive and more personalized. DVB-SH is provided with a very high bandwidth capacity that allows unidirectional IP-TV channels broadcast. We identified two scenarios of services that could be realized:

1. DVB-SH offers an important broadcast capacity. A residual bandwidth in the DVB-SH path may still be available because of the variable bit rates of served flows. Our first service scenario focuses on this small residual bandwidth and its potential utilization. The idea is to realize an efficient switching of IP popular services, coming from 3G networks, to the residual bandwidth of DVB networks. The goal is to use the architecture in order to provide interactive low cost services over DVB networks.
2. The second scenario considers classical DVB channels, including TV programs and advertisements spots. We enhanced such a TV service through the definition of personalized advertisements spots, that better fit user interests and localization. Obviously, advertisements are here given as an example of personalized service, but other types of contents could be proposed. In this scenario, the personalized content is sent over 3G, while the DVB content is still broadcasted. The terminal entity receives both contents, but plays only the personalized one. An important issue here will be the synchronization of flows to be read.

5.2.1. Coupling 3G with DVB networks for scheduled and non scheduled services

A residual bandwidth in the DVB-SH path may still be available because of the variable bit rates of served flows as shown in Figure 4. We focused on this small residual bandwidth and its potential utilization. The idea was to realize an efficient switching of IP data, coming from 3G networks, to the residual bandwidth of DVB Networks. The goal was to use this architecture in order to provide interactive low cost services over DVB networks.

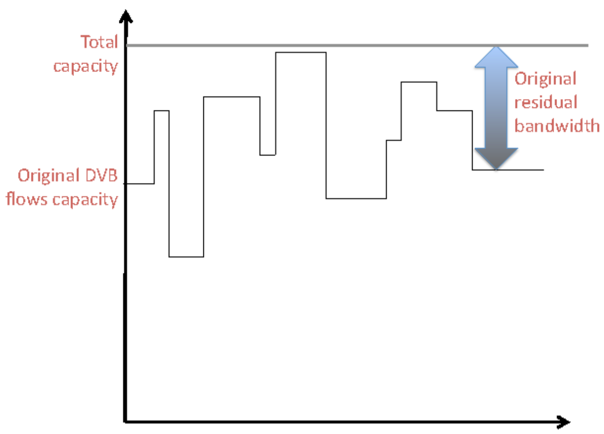

Figure 4. Residual bandwidth

Within this scenario, we proposed to manage two kind of 3G services: (1) *scheduled services* and (2) *non scheduled services*.
A scheduled service is a service whose availability is fixed and announced in advance. Users can subscribe in advance to the service. An important consequence, is that we know in advance if such a service is popular or not, thanks the number of subscriptions. 3G service providers ask for broadcasting their popular scheduled services over the DVB residual bandwidth. In a first step, we switched and inserted the 3G popular flows over DVB-SH residual bandwidth using a simple First In First Out (FIFO) policy. Then we refined our flow switching model through the definition of more adapted scheduling algorithms. Using Simulations, we showed that the delivery was a little bit delayed as the residual bandwidth is very small, however the service is efficient as it replaces numerous unicast connexions by a broadcast delivery over a bandwidth initially unused. Moreover, user are satisfied as such a service is offered at very low cost.
In a second step, we proposed to extend DVB residual bandwidth. Actually, 3G provider can pay for reserving some DVB channels. Our objective was to study the impact of this extension on the type and the quality of targeted services. This additive residual bandwidth allows to decrease the service transmission delay, and to implement "non scheduled services" not limited by availability announcement constraints. In this context, our study presented a user subscription prediction algorithm that aims to guarantee switching efficiency while maintaining service continuity. Thanks to bandwidth extension, the delivery delays have been reduced and our service could target a larger scope of services.

5.2.2. Customized content services

In this second scenario, we still considered a DVB-SH / 3G architecture, presented in figure 3. DVB-SH network delivers several TV channels. Each TV channel proposes many programs, which are broadcasted to all subscribers. The goal of this scenario was to enhance the offered service, by adapting some contents to make them fit user's interests and actual needs. Recent researches have considered the personalization of services and have proposed material solutions to provide regional content through DVB.

Our approach was different. Actually, we took benefit of the coupling between DVB and 3G path to provide personalized DVB TV contents. During the subscription process, users deliver their user profile, which indicates their main interests. During advertisement sequences, they continue receiving the DVB content, but, they also receive the 3G customized advertisement. Running some simulations, we observed that our scenario was not scalable as it involved too many unicast connexions thus prejudicing the performances of 3G "legacy" services. As a consequence, we changed our criteria of service personalization. Rather than using the user main interests based on its profile, we used user location. Actually, users sharing the same location have often similar interests. Users attending to a music concert are interested on music advertisements. Users attending to a football game are interested on football or other sports events, etc. We finally proposed to replace the 3G path by an MBMS network. MBMS environment provides the necessary tools to broadcast a unique content to all users located in the same radio cell. A different content can be delivered in each cell.

5.3. System architectures for pervasive computing

Participants: Michel Banâtre, Paul Couderc [contact], Guillio Zecca, Minh Tuan Ho, Michele Dominici.

We are interested in two aspects in pervasive computing: the first is pervasive computing system support, where we study how generic mechanisms based on physical structures and processed can be proposed. The second is the support for collaborative capture.

5.3.1. Pervasive support at core system level

Pervasive computing involves tight links between real world activities and computing process. While the perception of the real world events can be handled entirely at the application, we think that ad hoc approaches have limitations, in particular the complexity and the difficulty to re-use the code between applications. Instead, we promote the use of system level abstraction that leverage on tangible structures and processes. Important properties of this approach is that applications are, by design, operating in an implicit way ("in the background" of physical processes). They also often exhibits simpler architectures, and "natural" scalability in the sense that being build upon existing real-world process, they are strongly distributed design that relies essentially on local interactions between physical entities.

In this general principle, we proposed operating system level mechanisms based on pervasive memory to ensure data resilience and coordination support for robotic application, which is our contribution to the Roboswarm EU project.

5.3.1.1. Resilience for robotic

A swarm of robots needs to plan the tasks to achieve. This planning is a complex process and, when a failure occurs, a *replanning* is needed [20]. A *plan repair* first aims at reducing the costs of the new plan by deleting tasks or task parts already performed. This *plan repair* needs the knowledge about past actions. Classical works like ALLIANCE [21] do this *replanning* in a collaborative way using wireless technologies that enable all robots to stay in contact with each other. Other works like [20] address the issue of *replanning* without investigating the problem of availability of data for the *plan repair*.

This knowledge about past actions is very easy to get when a global network is available and when all the entities of the system have a permanent access to this network (like in ALLIANCE). However, this network may be hard or impossible to set up. For example, 802.11 coverage on a large field needs for access points to relay informations between areas. The deployment of those access points can be expensive (time and money consuming). In dangerous area like exploration area (space, submarine) or fields on fire, this deployment is even impossible. Therefore, new techniques are needed.

In the context of Roboswarm, collaborative backup greatly helps when a robot fails. It can reduce the costs of a failure without assuming the availability of a global wireless infrastructure. The deployment of robots is then easier and faster. As the main aim of this system is to reduce costs of the *replanning*, this system must give priority to expensive task and data. This system can also decrease the swarm needs for a centralized entity (like a global server).

We proposed and implemented such system, built using the opportunistic communication paradigm. We have simulated this backup system for swarm robots on some applications (cleaning and exploration) and shown that it reduces costs in the case of failure without interference with the swarm process.

This system tends to improve the process even more in the case of less centralized systems (multiple tasks attributed to one entity with possibilities of dynamic task rescheduling).

Instead of using other robots as backup storage, a pervasive memory addressed using near field communication can also be considered: RFID type memory tags can be arranged in the environment to ensure data persistence independently of the robots.

5.3.1.2. Local coordination

We propose a collaborative algorithm for a swarm of robots that have to complete a cooperative task after spatial and temporal synchronisation using RFID landmarks. The contribution to the Roboswarm project is twofold: we address the problem of collaboration, showing that the robots can actually fulfil a common coordinated task; moreover, we included this algorithm in a scenario where no central communication infrastructure is available, proving that the swarm can smartly accomplish some given goals just relying on robot-to-robot communication. We find the rationale behind that solution very important both for a fallback in case the central system fails, and for different implementations and future development of our system. The symbolic task chosen as example provides for the synchronization of a subset of the swarm, that have to collectively push a piece of furniture, to allow the cleaning in that area.

Our work focuses on the utilisation of RFID tags only in the synchronisation zones, where they are needed to fulfil a cooperative task, which relies on the coordination of the robots both in space and in time. Partial hints about the task to be done, or announcements from team-mates, are used to lower the time spent on this search phase by the robots roaming to find some additional information. Once a robot reaches a free tag, it can create an association with it, meaning that it is the only one agent exploiting the information stored on that tag, and acting consequently. This is named the "capture" phase. When a member of the swarm finds a tag, it publishes the coordinates of the previous and of the next tag. Hence all the other robots can dynamically update the list of available tags, and go towards the nearest one from their current position. This strategy drastically reduces the number of collisions without a considerable increase in the distance to cover. To correct the accumulated odometric error, the robot resets its odometry sensors to the position stored in the tag. This little correction is an example of correct exploitation of the "intelligence" scattered in the environment.

Despite the complications that may arise, distributed approaches to task assignment are generally preferred in Multi-Agent Systems for several reasons, such as robustness to single agent failures, scalability of the system, time constraints of applications, constraints on communication load and computational power of the agents. Whenever an agent accomplishes a task, it announces its termination to the entire team, even though simultaneous tag discovery and asynchrony among messages can lead to some conflicts. During the development of our solution we considered a self-stimulation mechanism similar to the proposed one to invoke a group behaviour in all robots receiving that clue.

Coordination can be seen as divided into two levels: space, because robots must be in a pre-determined formation to trigger the start; time, because robots must synchronise to start together. The configuration seems to naturally rely on multi-hop message passing; however this was quite heavy and not so robust. Indeed, a lot of information must be exchanged to have updated and accurate data, and since the robots are mobile, we cannot waste resources, be they computation cycles, battery or others. Other strategies like gossip dissemination were neither so immediate nor so convenient to be implemented on simple robots that are unaware of the external world. The communication exploits thus a hybrid fashion between multi-hop and probabilistic flooding, so that each robot receiving an announce forwards it in its "broadcast bubble" described by its communication range and physical obstacles. This may not be the best strategy to optimise energy, but it is very probable that all the members will get the message, even the ones which are not in the coverage radius of the sender, and that are necessary for the outcome of the task (see Figure 5).

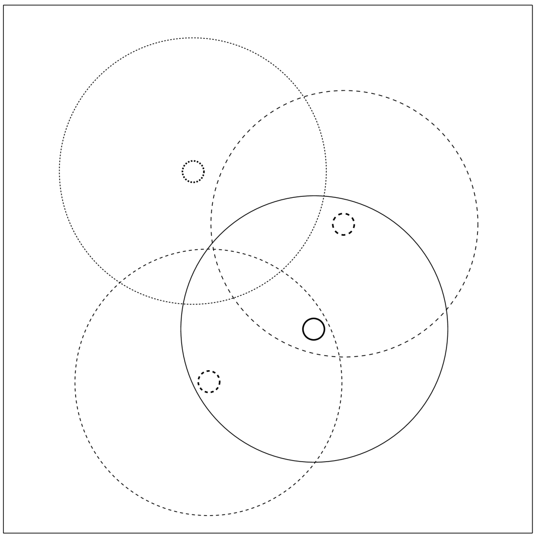

Figure 5. Robots (small circles) and their relative broadcast bubbles

When a robot captures a tag when no global communication infrastructure is provided it could be unaware of the state and activity of the other members of the swarm. It might have missed the announcements from its team-mates, so it could be the first one, an intermediate one or the last one discovering a synchronisation zone. The first thing to do is to communicate that a tag is there, and has been captured. In this way, the other robots who are still roaming will have a more accurate clue to find the target zone, and the ones that already captured a tag can announce their state to allow the upcoming robots to upgrade their vision of the world. The main problem of the algorithm is to have a synchronised trigger of the task, even with a minimal delay due to the goal type and the distributed nature of the task. The developed algorithm was conceived on the base of the Two Phase Commit protocol (2PC), quite used in distributed environments. In our case, the "ready to start" is given by the physical arrangement of the robots on the tags. Though all the robots act in the same way, one of them must take command for a while to grant a correct execution of the protocol.

To ensure that as many robots as possible participate in the collaboration, the leader waits for the capture of the other tags for a reasonable timeout. Afterwards, if at least the minimal number of robots are active on a tag, it broadcasts a message warning that the swarm is ready to start. Each robot receiving the announce retransmits the message, and checks which robots are on the previous and on the next tag, to create a kind of topology structure, needed afterwards for the control phase. When all the robots are ready, the leader commits the time to trigger the start.

We provided some simulations to ensure an opportune outcome. Finally, our proposal has been validated with qualitative and quantitative metrics on the distance run and the exchanged messages. The results showed that this kind of approach is practicable and that can be implemented in real life, and the implementation of such a system for operations like cleaning or equivalent is foreseen for the near future. The futuristic field of space exploration, together with the idea of setting up space colonies, is currently under research; the coordinated movement and the synchronisation among robots are definitely in scope.

5.3.2. Collaborative capture

The ubiquity of personal multimedia capture devices such as mobile phones brings new opportunities, such as the novel concept of *collaborative* or *distributed capture* [14]. Distributed capture consists in using a collection of personal devices dispersed throughout to capture data of an event or a reality as a distributed sensing infrastructure, and exchanging and synchronizing the resulting aggregate to increase the global quality.

An important challenge raised by this concept is to ensure coherency of the data being captured when merging fragments. For example, merging an audio stream captured by a device with a video captured by another raises temporal coherency issue [14]. Another example would be a swarm of robots collecting data using their onboard sensors, in order to make a map. This application raises spatial coherence issue as the spatial references of the data collected by an indivudal robot are dependant on sensor accuracy, such as robots odometry.

We are working on the problem of spatial coherence in the context of a collaborative photographic application, inline with the previous research. In such application, a mobile device can take pictures and reference the distance and the direction relatively in between the spots where the pictures are taken. In this way a map can be built of the environment wherein the photos are related by their distance and relative direction (angle). This information can be shared between users and this collectively built map can then serve as a photographic guide to others. One can expect the map would grow quite big easily, so the application should scale well to large collections. It makes sense to distribute the geotagged photo collection and any processing involved in locating and relating the pictures, so resources can be shared in a way that is achievable for limited mobile devices and without a central service.

A first approach was proposed to deal with spatial coherence issues that arise because of inaccuracies in the users estimates in this distributed capture example application. Distributed photo capture more specifically concerns the aggregation of photos taken with a mobile device, by several users and at different but related places, into a coherent collection. The coherence of the collection is clearly the quality metric here. A photo collection becomes spatially incoherent when a photo is added that is not at the location where the user expects it. Based on the virtual world model of the collection, the user might expect to see one thing but might get to see something quite different that does not match reality. The solution we proposed consists in a distributed algorithm that spread the errors by relaxation. [9]

5.3.3. Definition of a proactive service

Devices such as mobile phones are the main interaction point for mobile users. We studied the possibilities offered by these devices within the framework of a museum. Two classes of interactions can be considered:

- Visitor requesting information from the site: a visitor uses an interactive service to receive a list of recommended objects. It explicitly requests information from these objects in the museum. These interactions can be seen as "pull" type. The visitor carries a mobile device, offering him access to web-type information system in a contextual manner: requests include context descriptors such as current position or user profile that can influence the available information or its presentation.
- Visitor automatically receiving contextual information: a proactive service senses the environment and spontaneously adapts its behaviour to the local context. These interactions can be seen as "push" type. Typical sensing involves determining the profiles of near by visitors, allowing the dynamic computation of group profiles and enabling global adaptation of the environment. For example, if a room uses vocal explanations or shows short documentation movies, environment sensing enables automatic selection of the dominant language accordingly to the current visitors in the area.

Typical sensing involves determining the profiles of near by visitors, allowing the dynamic computation of group profiles and enabling global adaptation of the environment to the context. The notion of "context" considered here refers to a description of a physical situation in the museum; a physical situation may be described by low descriptors such as raw sensor values (GPS position, RFID, etc.), but these one are usually not directly relevant for an application. Context-awareness requires higher level description that can be used easily by service. For example, an application shouldn't have to do only position computation if the goal is to determine what is the language spoken by nearby people. Instead the application should be able to request data matching some criteria, including spatial properties if required.

We designed a context-sensing information diffusion system to detect and identify group of users (co-located in a given area of the museum), and to provide them with unsolicited messages like "conference invitation at 14pm, room 12", with a multi-language support, and multi-modal support (Text To Speech is automatically activated for people with visual disability).

Two aspects have been addressed:

- First the service requires determining visitor's context in a given spatial area of the museum. For that, two kind of information are required: visitor's localization and personal parameters like "spoken language" and "ability to see". Localization can be accessed using RFID reading, combined with WLAN connectivity. Personal parameters can be extracted directly from profile stored in mobile device. Of course collecting these data in museum environment is a privacy concern, as it potentially enables visitor tracking when associated with user's account. So we only use "anonymous attributes" of the user's profile such as "language spoken", information sent by device application is not associated with user's account.
- Second a provisioning strategy is decided to target visitors in an efficient way. By efficient, we mean allocating the collective resources (for example, monitors in the museum) to larger groups (the "major" spoken language), and using mobile device for smaller groups. For that, we use the majority rule: the collective devices is allocated to display message in "major" language, while messages in "minor" languages and messages "compliant with Text To Speech engine" for users with visual disability, are forwarded to smartphones.

5.3.4. Coupled Objects

The concept of *coupled objects* 3.3.3 is a simple yet powerful pervasive computing approach to check or ensure integrity properties in real-life. In can be used to check for lost objects, to avoid or reduce thieft, to provide integrity checking and accountability in logistic and so on.

We developed the Ubi-Check system, which allows to ensure that a set of physical objects remains complete as it enters or leaves controlled area. A particular application of the system finds its way for airport security: objects or tools that are not authorized in boarding area are still introduced by workers operating maintenance in these area. Ubi-Check can ensure that a set of objects that has entered the area is complete when it leaves the area. This application will be experimented at the Geneva airport.

We also developed and experimented several advanced prototype applications for the logistic domain. With the development of E-commerce, a difficult issue is rising: ensuring that a package that is delivered to its destination match the recipient expectation, and ensuring accountability in case of a problem. Currently, when a package is not complete once shipped, it is difficult to determine whether the fault was from the sender, the recipient, or at some level during the shipping. Coupled objects offers an elegant solution to this problem, mostly transparent to the information systems of the different parties involved in the process which is a major point: as the system relies on data structure self contained into the physical objects being transported, the integrity properties can be checked in an autonomous way. This system, Ubi Post, is currently the object of discussion with potential industrial users.

5.4. Information System Processes

Participants: Ciáran Bryce, Pierre Duquesnes.

A fundamental feature of software today is that it continuously needs to be modified – even after its deployment on client or server machines. Modifications might follow the appearance of new business requirements, the need to adapt the software to new hardware, or the need to re-engineer the software for efficiency or licensing issues. Urgent software modifications may also appear in the form of fixes for security holes and bugs. In today's world, the facility to modify existing software is as fundamental a requirement as the facility to build software in a modular, reusable-component fashion.

One of the founding principles of the object-oriented programming paradigm is inheritance. This technique enables a programmer to take a software component, and to design a new component based on this. For instance, a Double is a floating-point arithmetic concept that is built from the Number concept, with additional functionality. However, Double is an extension of Number; client systems that use Double are unaware of the new concept. Inheritance means that the new concept retains the inherent characteristics of the old concept. This is too restrictive for the bug fixes and the range of software modifications that need to be envisaged. The aim of inheritance is software extension; this is not the same requirement as software evolution. A mechanism is required for object-oriented systems that goes beyond inheritance.

Software systems are traditionally updated by applying a patch to the program binaries, and then rebooting the system. However, this supposes that the system can be stopped – something not evident for software that needs to run 24/7. Some servers get around this issue by tolerating minor interruptions and/or by duplicating hardware so that servers can be restarted independently in a cascading manner. Neither solution is complete satisfactory. Even more fundamentally, there is no model to guide the design and application of a patch from the original source code in a manner that the programmer can reason about the way the modification is applied, and the behavior of the system after update.

There has been some work on dynamic software update, where a modifications are made to programs while they execute. These approaches generally seek to replace functions or methods in running programs. The approach has the advantage of seeking to make program update usable in legacy systems. However, the approach does have complexities. First, in practice, the nature of modifications to be made might not be confined to the function or class. Second, function and class replacement is particularly hard to implement due to the risk of typing errors, synchronization errors, the presence of long-running functions like main.

Our work presents a language model for dynamic program update. The model permits a programmer to define stages of computation. Control flow passes from stage to stage, and a program update is modeled by funnelling control to a new set of stages. Making update explicit in the model helps avoid the complexity of existing dynamic software update methods. Further, the model allows the programmer to specify changes that can be made at program update as expressions in source code.

6. Contracts and Grants with Industry

6.1. National contracts

6.1.1. TV mobile <<sans limite>> (TVMSL)

- Partner : Alcatel Mobile Broadcast, Alcatel Alenia Space Alcatel, DiBcom, Sagem Communication, TeamCast, Radio Frequency Systems, UDcast, CEA-Léti, Inria-Rennes, CNRS-L2S
- Starting: 01/11/206, ending : 30/04/2009

The objective of this contract is to design and evaluate inovative caching mechanisms to distribute H.264 flows in future hybrid DVB-H+ infrastructure (satellite + terrestrial).

6.1.2. Définition d'un service de gestion de l'énergie dans le cadre de l'habitat résidentiel en s'appuyant sur les principes de l'informatique diffuse : études préliminaires

- Partner : EDF - DER
- Starting: 01/05/2009, ending : 31/12/2009

The objective of this short project is to study the use of ambient computing principles for the management of electricity consumption in residential habitat. The objective is (1) to define scenarios based on home people activities, and (2) to propose an implementation of these scenarios using ambient computing mechanisms studied in the ACES project. This first phase must be concluded by a final report, in order to decide if a partnership much more ambitious between INRIA-ACES team and EDF-ICAME is possible.

6.1.3. Système d'Information Voyageur Embarqué : SIVE

- Partner : Kerlink, Innes, Loustic
- Starting: 01/12/2008, ending : 01/05/2010

The SIVE project aims to create an embedded information system for public transportation users. The project mainly focuses on inner-city and inter-city transportations such as bus or subway. Information received by the users are multimedia, context dependent and customized. Considered means of diffusion are various such as screens in a bus or users' cellphones.

7. Other Grants and Activities

7.1. European actions

7.1.1. European Project: Roboswarm

- Title: Robot Swarms
- Proposal/contract no: 045255
- Tallinna Tehnikaulikool- Estonie, ELIKO Tehnoloogia Arenduskeskus- Estonie, Institut National de Recherche en Informatique et en Automatique- UR Rennes, TEKNILLINEN KORKEAKOULU- Finlande, OULUN YLIOPISTO- Finlande, FUNDACION FATRONIK- Espagne, KTH - Kungliga Tekniska Hogskolan Royal Institute of Technology- Sweden, IDMIND-ENGENHARIA DE SISTEMAS, LDA -Portugal, Universita degli Studi di Genova -Italie
- Starting: November 2006, ending: April 2009

Roboswarm is an EU project that started in November 2006 in which ACES is a participant. The goal of the project is to develop an open knowledge environment for self-configurable, low-cost and robust robot swarms usable in everyday applications. Advances in the state-of-the art of networked robotics are proposed through introduction of a local and global knowledge base for ad hoc communication within a low-cost swarm of autonomous robots operating in the surrounding smart IT infrastructure. The ACES group was invited into this consortium due to its experience with ad hoc (ambient) network environments.

7.1.2. Smartmuseum

- Title: Smartmuseum
- Partners: Competence Centre of Electronics-, Info- and Communication Technologies, ELIKO (Estonia), Helsinki University of Technology TKK (Finland) Kungliga Tekniska Högskolan KTH (Sweden), Webgate JSC, (Bulgaria), Heritage Malta, (Malta), Institute and Museum of the History of Science, (Italy), Apprise, (Estonia).
- Starting: end of 2007; ending: December 2010

The general objective of the SMARTMUSEUM project is developing solution and IT services for user interest dependent (profiled) access to digitalized cultural information that is relevant in particular physical location. The activities of the project are addressing personalised approach to cultural exploration, including cultural tourism. The future smart museum IT infrastructure and services, which are capable of increasing bidirectional interaction between multilingual European citizens and cultural heritage objects taking full benefit of the multi source digitalized cultural information. By doing this, priorities are set on: Improving structured and user competence dependent access to the vast repository of cultural heritage, Improving the meaning and individual experience people receive from cultural and scientific resources, Bringing personalized cultural experience closer to non-expert community, Making real reuse of experiences related with cultural heritage access for variety of interest groups.

7.1.3. NoE Resist

- Title: Resilence and Survability for IST
- Head: LAAS
- Starting: beginning of 2006; ending: March 2009

The NoE ReSIST (Resilence and Survability for IST) will focus on the following four objectives in addressing the scalability of dependability and security via resilience:

- Integration of teams of researchers so that the fundamental topics concerning scalably resilient ubiquitous systems are addressed by a critical mass of co-operative, multi-disciplinary research.
- Identification, in an international context, of the key research directions induced on the supporting ubiquitous systems by the requirement for trust and confidence in AmI.
- Production of significant research results that pave the way for scalably resilient ubiquitous systems.
- Promotion and propagation of a resilience culture in university curricula and in engineering best practices.

Michel Banâtre is the scientific leader of the Work Package 2, which is the "more research oriented" work package of the RESIST NoE.

7.2. French initiative for research in security and informatics

7.2.1. Region: P2PImages

- Title: Privacy in Ambient Computing Systems
- Partners: ENST Bretagne, France Télécom, CREM, IRISA/INRIA, IPdiva, Mitsubishi Electric, THOMSON.
- Starting: October 2007 to October 2009

The goal of P2PImages is to investigate the design of platforms for legal content exchange in peer-to-peer environments. The goal of Aces in this project is to study digital rights management issues.

8. Dissemination

8.1. Animation of the scientific community

8.1.1. Program committees

- PC member of 2009 IEEE Second International Workshop on Specialized Ad Hoc Networks and Systems, M. Banâtre.
- PC member of 2009 7ème Conférence Française sur les Systèmes d'Exploitation, F. Weis.
- PC member of 2010 International Conference on Ambient Systems, Networks and Technologies (ANT-2010), M. Banâtre.
- PC member of SEUS 2009, The Seventh IFIP Workshop on Software Technologies for Future Embedded and Ubiquitous Systems November 2009, Newport Beach, CA, USA, P. Couderc.

8.1.2. Organizing and reviewing activities

Michel Banâtre is member of the "Comité d'Evaluation des programmes" ANR and member of the expert scientific committee for ECOTECH (Production Durable et Technologies de l'Environnement).

8.1.3. Thesis committees

Michel Banâtre was in the examination committee of the following Ph.D. thesis: Frédéric Lassabe, "Géolocalisation et prédiction dans les réseaux Wi-Fi en intérieur", Université de Franche-comté, 2009 (referee).

8.2. Teaching activities

- IFSIC, Responsibility of the lecture on Ambient Computing and Distributed Operating Systems in "DIIC 3 ARC" (final year of masters) (M. Banâtre, P. Couderc and F. Weis).
- IFSIC, 6 hours of lectures on Ambient Computing and Mobile Communications in final year of masters (M. Banâtre and F. Weis).
- Ecole des Mines de Nantes, Responsability of the lecture on distributed systems (final year of masters) computer science department (M. Banâtre).
- INSA of Rennes, Responsibility of the lecture on Ambient Computing and Distributed Operating Systems (final year of masters) computer science department (M. Banâtre).
- ENST Bretagne, Lecture on Wireless LANs (final years of masters) (F. Weis).
- ENSEIRB (Bordeaux), Conference on Mobile communications and ambient computing, final year of masters, November 2009 (M. Banâtre).
- École Centrale de Paris (ECP), Conference on Mobile communications and ambient computing, final year of masters, November 2009 (M. Banâtre).
- École Centrale de Paris (ECP), 6 hours of lectures on Mobile communications and ambient computing, final year of masters, March 2010 (M. Banâtre and F. Weis).

8.3. Internship supervision

We have supervised the following internships in 2009:

- Nadia Jemel (2nd year ENSEIRB sutdent). Subject: implementation of a "push based" mechanism for the SmartMuseum project.
- Rachid Ajala (2nd year ENSEIRB sutdent). Subject: GUI for Ambient Computing.

8.4. Seminar

- Informatique Diffuse : des concepts aux applications, Intelligence Ambiante, école thématique, Lille, July 2009. (Michel Banâtre)
- L'informatique diffuse : Ingrédients et applications, 14eme forum pour les NTICs dans le Transport, ESIEE, Noisy Le Grand, May 2009. (Michel Banâtre)

8.5. Patents

Michel Banâtre, Paul Couderc, Mathieu Bécus, Dispositif et procédé de vérification d'intégrité d'objets physiques, n.INPI, 08/02783; May 2008, extended in March 2009.

8.6. Industrial transfers

Throughout 2008, in accordance with the goals of the Institute, the ACES group spent a great deal of time and effort on seeking to transfer its research results on ambient computing to potential users. We sought out and negotiated with representatives of end-users in advertising and the urban construction industries. Our motivation stems from our observation that producing innovative research results, even those protected by patents, is no longer sufficient for a modern research team. It is essential to convince industry that solutions are robust, scalable and most importantly, address a problem that real users are faced with.

This research approach necessitates the development of several prototypes that are tested in real environments. It also necessitates a continuous technology watch to ensure the validity of submitted patents, as well as verification of existing patents and research reports. Although this activity is, traditionally, unusual for a research team, it becomes inevitable if results are to have a real impact in the ambient computing applications currently being deployed.

Our technology transfer efforts have been successful as a part of ACES group created a start-up company called SenseYou last july. Its main business is based on the exploitation of INRIA patents and software dedicated to contextual information systems. In the same time ACES members continue their efforts in order to identifiy industrial partners able to exploit the potential indusrial transfert behind their new ideas about "physical coupled objects" and their application in security area. To do that, ACES group built a big prototype to emulate an airport boarding room. This prototype was demontrated during the big show, "La ville européenne des sciences" in "Le Grand Palais" Paris, last november. More details about this prototype can be found in a video: Ubi-Check", Michel Banâtre, Paul Couderc, Fabien Allard, Mathieu Bécus, INRIA Dircom-Multiédia, November 2008.

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[2] D. MARTIN-GUILLEREZ. *Mécanismes de prise de points de reprise opportunistes pour robots mobiles autonomes*, University Rennes 1, July 2009, Ph. D. Thesis.

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