The uPart experience: Building a wireless sensor network

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ABSTRACT
This paper presents an experience report illustrating the design of the uPart tiny low-power sensor network platform: from the analysis phase over the definition of the application, design and construction of hardware, the implementation of the software and network to the application set-up. uPart sensor nodes were given away in the conference badge to 500 voluntary attendees of the Ubicomp 2005. In our demo application, uParts were able to recognize activities of attendees of the Ubicomp 2005 conference. Design was carried out under serve time and budget restrictions. The paper focuses on reporting design decisions and presents technical details of uPart hardware, firmware and applications. It also shows first qualitative experiences with the run of the system at the conference. The outcome of the paper is a general meta-guideline for designing sensor network systems under similar conditions**.**

Categories and Subject Descriptors
C3 [**Special Purpose and Application Based Systems**]: *Real-time and embedded systems**, Microprocessor/microcomputer applications***

General Terms
Design, Experimentation, Human Factors

Keywords
uPart, system design, experience report, sensor network platform, wireless sensor network development.

1. INTRODUCTION
This paper describes the design, construction and parameters of a sensor network platform, the uParts. The paper presents an experience report how we build the uPart sensor platform and its application starting from the analysis of the intended application setting and ending with first qualitative experience with the run of the system. The paper not only describes the platform itself but also motivates and reasons design decisions while developing this sensor network platform. The application setting for this platform development was the detection of activities from (almost) all attendees of a larger scientific conference. This paper will discuss the general application setting and its parameters, hardware design decisions as a result of the application setting, software design decisions, network design decisions, application design decisions and gives some first experiences from the run of the system at the conference.

2. INITAL IDEA
The uPart platform was handed in as a demonstration proposal to the Ubicomp 2005, a conference with more than 500 attendees. Our intention was to demonstrate a small and easy to use sensor network platform and its deployment. We planed to hand out small wireless sensor nodes to every attendee of the conference if possible. These wireless sensor nodes should then be worn in the badge (see figure 1) to continuously monitor activity of the person, but also to recognize activities around that person. Attendees should benefit from the system by using several applications from terminals on our demonstration booth or on their personal computing device. For example we enabled users of the system to access their individual behavior data by using their PC, PDA or mobile phone. The system was also open so that other researchers were able to use the information for their own purposes through simple to use interfaces.

Figure 1. uPart wireless sensor node in a conference badge

Apart from presenting our technology to attendees of the conference, our intention was to collect experiences with large-scale sensor network technology and collect input data for later off-line network simulation. We also wanted to build up a large sensor database and collect activity data for later re-use. We intended to use this dataset later for use in context recognition simulations. As we were not sure what exact data would be needed afterwards our approach was to collect as many data as technically possible from the setting. The analysis of this data is ongoing and not presented in this paper.

3. ANALYSIS

3.1 Site and venue
The conference was divided in 3 main events blocks: Workshops and Doctoral Colloquium that took place at the first day of the conference (Sunday), Technical and video presentations scheduled for roughly 9-18 on Monday to Wednesday of the conference and interrupted by lunch (about 12-1pm) and coffee breaks (roughly 10:15-10:45 and 15:00-15:30 every day). Additionally there were evening events outside the conference hotel on Mon-

day and Tuesday. All other events except the Workshops, Doctoral Colloquium and lunch were held in one contiguous large space at the conference hotel.

The conference space was divided into 2 areas: The main presentation hall where the technical paper and video presentations were held and the demo & poster space. This area was located in the basement of the conference hotel. The space did not have any windows and was illuminated by artificial light only. Demo and Post space was itself separated into two rooms plus the main entrance hallway. In the hallway some of the poster and demos are presented, but also the registration and information desk was located there. Coffee was served in the hallway and the main presentation theater. Floor space of the main theater was about 35x35 meters, the demo rooms where about 25x25 meters and 15x15 meters respectively. The hallway was about 40 meters long and about 15 meters wide. Workshop, doctoral colloquium space and lunch were held in a separate area of the conference hotel, about 200 meters walk away from the main conference site and on a different floor level. In total the whole area measured about 3000 m².

We decided to have network coverage only for the main conference site as it was unclear if we are allowed to install equipment on the external walkway to the lunch area. To ensure continuous monitoring we decided to design a software buffer solution to collect data outside the coverage of the uPart network for one to two hours. This also enables us to track activities when attendees leave the conference site e.g. to go outside for smoking, going to the coffee area etc.

3.2 Attachment of nodes and selection of detected activities

Sensor nodes should be worn in the conference badge by attendees. This option was without alternative as any other place would force us to provide a housing for the sensor node. This was seen as impossible in the short timeframe considering the large number of devices and the cost. It was unclear until set-up time of the conference, if the sensor node is worn on the front side (sensors visible) or on the back side of the badge, so sensor had to be designed to support both types of attachments of the uPart in the badge.

The Sensor nodes should detect activities of attendees and possibly situations in the environment. We liked to get information of 3 conditions: Motion activity of the attendee, general situation and coarse grained location information of the attendee. Examples of situation information are “inside in bright light” (poster and demo area), “insight in dimmed light” (presentation area) and “outside a building and surrounding condition”. We therefore measured three physical parameters: Movement of the sensor node, light condition, temperature for recognizing general environment conditions and cell of origin (COO) of the wireless RF network.

3.3 Timeline and Set-up

The time span between notification of acceptance for demonstration to the conference was about 7 weeks. This puts an additional logistical burden to the demonstration as the hardware platform has to be received or produced and shipped in this timeframe - to avoid unnecessary production of hardware. We therefore initially decided to concentrate operation of the application on the main event times from Monday to Wednesday only to decrease logistical burden for us. This turns out to be a good decision as we were required at the end to set up our infrastructure together with the Wifi and other network on Sunday. Nevertheless, first nodes should be given out and be activated on Sunday morning - e.g. to the volunteers - and should run until Wednesday evening a least. As a consequence battery lifetime has to be designed to let the uPart operate for at least 5 days.

4. HARDWARE PLATFORM DESIGN

4.1 Sensor nodes selection and design

We intended to give out sensor network devices to potentially all attendees if possible. This required a large number of devices as the expected number of attendees was 500 or more. At maximum the conference site was able to host about 650 attendees.

We considered several options to be used as sensor nodes. One option was using an existing, already settled and produced design as the TecO Particle platform or similar sensor nodes as MICA [8] or Telos (see e.g. www.xbow.com). The advantage of these platforms is their proven functionality for a longer period of time and simplified application design due to existing libraries and tools. The disadvantage of these options from our experience is that these are still complex systems both in hard- and software. This could lead to side effects difficult to debug and detect, but also adds additional point-of-failures to the overall system.

Also, we planned to use small of-the-shelf coin-cell type batteries and continuous operation over 5 days minimum. Lithium based coin cells have severe restrictions due to peak power and continuous power consumption. For cell types smaller than 20 mm in diameter (this was seen as the maximum diameter size for the node, see below, possible standard types are CR1620, CR1632, BR1620, BR1632) peak power consumptions of more than 25 mW and continuous power consumption over 1 mW destroys the battery in a few hours. These measurements were taken by us using several batteries of CR16xx types from different producers. Datasheets specify even severe restrictions for proper usage.

Peak Power consumption of Mica and Telos nodes was seen as too high. Another excluding factor for the use of existing sensor node platforms was size (Particle 45x18mm or MicaDot 25x25mm without battery) and price (>60 Euro). After asking organizers at the Ubicomp about intended badge size we ordered some badges for experimentation. Our experiments showed that the maximum outline should not exceed 20x20x6 mm including battery. Larger outline would lead to covering large parts of the badge or deform the badge. We finally decided to develop a hardware design specially suited for the application we had in mind. To save development time we started with an old experimental design for a small (10x10x10mm) sensor node, the uParts. uParts where initially designed as a sensor node study and had a flexible 2-board approach to separate the sensor and computation/ communication part. Because of the selection of sensors, the cubic outline and because the old uPart could not be produced in an industrial process the old uPart version was not suitable for the demonstration application and required a redesign. The hardware design had to follow the following requirements that we found most important in our case:

- Physical outline: Small and flat outline to be put into badges,
- Cost: Low-cost-production, 0-configuration, 0-maintanance
- Production: Simple to produce in an automated process (we had only 6 weeks for producing and shipping)
- Robustness: to avoid maintenance (mechanically, electrically, but also software later on)
- Standard: Use of standard batteries as these should be bought at the conference place, use of standard components due to tight timeline.
- Coin cell operation: All components on the hardware should have a wide voltage range around 3 V and should have low power consumption.

Sensor design. Because of the initial decided activities to be detected a movement, light and temperature sensor should be assembled onto the uPart hardware design. This decision was founded on former evaluation of sensors needed in such settings [2]. For the movement sensor we found following requirements as most important: simple-to-evaluate (because of low software complexity needed for the short time of development), low-cost, low-energy, high sensitivity (to detect movement activities). The light sensor should be suited to sense in-house light conditions (technical properties sensitivity, frequency spectrum). Because we did no know if the uPart would be placed in front side (sensor visible) or back side (sensor covered) of the badge, the sensor should have a wide sensitivity angle. Also, low energy consumption and low cost was an issue. Temperature sensors often require long start-up times which increases the overall power consumption of a sensor node. Short start-up time but also general low-energy consumption and low cost were seen as critical here. Overall, sensors should not require additional circuitry due to board space and complexity, they should be easily available and simple to produce in an industrial process.

All sensor used in the original old design of the uPart failed short in one of these categories. After this analysis we decided to revise the complete initial sensor design of the uPart to be more appropriate for the application setting in mind.

Sensor name	Typ. (mW at 3V)	Max (mW at 3V)
Voltage	0.03	0.045
Temperature	0.105	0.195
Movement	0.003	0.006
Light	3.3	5.1

Figure 2. Sensor power consumption

Motion sensor. Motion was seen as most important for detecting human activity. One option we considered was the use o an acceleration sensor. Such a sensor would allow us to sense fine grained movement information data and was initially seen as the sensor of choice for movement activity recognition. On the negative side an acceleration sensor requires constant polling of the sensor, higher power consumption of the chip, long start-up times and more complex computation. We finally decided for a ball switch sensor. We tested several types of ball-switch sensors and found that all off-the-shelf sensors on the market are inappropriate because of size or sensitivity. We finally selected a (digital) micro-machined ball-switch sensor prototype developed at an Institute associated with our University which perfectly fitted our needs. The function principle of the ball switch sensor is a tiny golden ball that is rolling up and down the miniature space inside the ball-switch. Detection is done by detecting the ball contacts any side of the ball switch.

Due to the low mass, the ball switch is very sensitive to even slightest movement or vibration if used with component side upwards. When the uPart is tilted so that the component side is not absolutely horizontal sensitivity is reduced. If the uPart is tilted more than 90° so that the battery side is showing upwards, the movement sensors sensitivity degrades to 0. We deliberately assembled the ball-switch, so that if the sensor node is worn in the badge the sensor is used in 90°. This avoids that due to the high sensitive even slightest movements where detected which would put too much burden on processing data too often, and, as a consequence reducing our sleeping time thus increasing energy consumption. This decisions can be seen as a trade-off between more accurate human activity detection and power consumption.

Light sensor. We initially started with a "smart" light sensor with I2C interface that provided us precise light measurements. Although this allows us to apply the sensor in various settings, we suffered from the memory and computation resource consumption required by the I2C protocol and the handling of the registers of the sensor. We also found that high precision was not required for our application. We finally decided for the TSL13T from Taos Inc. The sensor is a mid-sensitive analog light sensor with a linear output voltage of 24 mV/(µW/cm²) at λ = 640 nm especially suited for in-house light condition. The highest sensitivity of the sensor is about 750 nm, but good sensitivity (>50%) can be obtained from a spectrum between 550 nm and 900 nm. The TSL13T covers a total spectrum between 320 nm and 1050 nm. The TSL13T is most sensitive for light directed towards the sensor (0°). The sensitivity drops only slightly when light is directed with larger angles. 50% sensitivity can be obtained between -70 and +70° angular displacement of sensor and light beam. This characteristics is very suitable to detect various lightning conditions inside buildings, but saturates under daylight conditions. The large angle allowed us to place the sensor node on the back or front side of the badge without much detection difference. This characteristic is almost perfect for our application setting as it allows to easily separate talk, coffee-break and outside conditions.

Temperature Sensor. From the numerous temperature sensors we selected the TC1047A temperature to voltage converter from Microchip as a temperature sensor. Although the sensor is rather simple, it provides rather high accuracy and allowed a simple handling of the sensor from the microcontroller. The TC1047A is specified for ±0.5°C accuracy (typ.) with a linear temperature slope of 10 mV/°C and a total operating temperature of -40°C to +125 °C. The short ramp-up time of under 1 ms allowed us to conserve power even with short duty cycles.

All sensors consume low power, an overview of typical and maximum power consumption can be found in figure 2. All of the sensor above are very low-cost, operate between 2.7 and 3.3V, could be placed on the board and soldered using automated processes (SMD) and – with the exception of the motion sensor - are off-the-shelf parts. This fits our needs for fast production and requirements for battery powered operation. None of these parts requires additional circuitry which was a necessary issue to save board space and meet the outline conditions.

Actuator. To simplify identification of malfunctioning nodes a simple, but energy saving actuator was needed. We decided for a ultra-low-power red LED that was directly coupled to the power of the RF unit. This way we received reliable information about the central feature of the system, the communication.

4.2 Communication and processor hardware requirements

Processor. Requirements for the processor were low power consumption, small outline, with enough internal program memory to perform simple computation, networking and enough internal data memory for buffering data in case of network breaks (see requirements from the application below). To save board space no external circuitry or components for memory, I/O, power regulation etc should be required. The processor should be easily available and simple to produce in an industrial process.

Communication hardware. Also the communication hardware should be robust, small, with low power consumption and at best adjustable for several frequencies (at least in hardware) to allow us some flexibility in the hardware design. Complexity of the hardware design should be as low as possible.

SYMB.	CHARACTERISTIC	MIN	TYP.	MAX	UNIT	CONDITIONS
			0.8	2	µA	CPU sleep, Analog, RF switched off
I_{DD}	Current Consumption at 3 V	-	340	1000	µA	Analog Sensors switched off, RF switched off
		-	1.5	2.5	mA	Analog Sensors switched on, RF switched off
		2.0	3.2	5.7	mA	RF Ouput Power = -70 dBm
		2.9	4.0	7.7	mA	RF Output Power = -12 dBm
		3.2	5.2	8.6	mA	RF Output Power = -4 dBm
		4.5	7.0	11.7	mA	RF Output Power = 2 dBm
		7.0	11.2	16.7	mA	RF Output Power = 9 dBm

Figure 3. Current consumption of the uPart under various conditions

Decision. We decided for a chip with integrated processor, memory, I/O and RF transmitter, the rfPIC 12F675 from Microchip (www.microchip.com) for the sensor nodes. The chip fulfilled all the above requirements, but a consequence of this low-cost, low-complex design was that the chip provides only limited resources., The RF part of the chip allows to use either 2FSK or ASK modulation for data transmission. The memory part of the rfPIC 12F675 has 1.4 kByte Internal Flash for programs, internal data SRAM of 64 Byte, and internal data EEPROM of 128 Byte. The internal oscillator of the CPU operates at 4 MHz (equally to 1 MIPS), has 6 general purpose I/O, 4 of them analog inputs. The integrated RF unit can be used in a wide range from 300-950 MHz (various rfPIC versions), transmitter frequency is controlled by a external crystal. For the demonstration we configured the uPart to use the 315 MHz band, a Japanese ISM band.

Antenna. The design of the antenna is critical for the performance of the communication. Possible options where chip antennas (too poor performance and high price), coil antennas (poor performance and large outline), PCB antenna (impossible for the 315 frequency range s this would triple the size of the sensor node) and wire antennas. From all options, wire antennas, even if knotted in awkward ways showed by far the best performance. We decided for this option although we initially though the long antenna wire would be distraction for the potential users of our sensor nodes.

Board design. The initial uPart was designed as a 2-board solution decoupling the sensor and the computing/communication part. This approach had several disadvantages for the proposed demo application. First, 2-board designs are thicker and are therefore not well suited to fit into a conference badge. Also, the connector between both boards is a critical mechanical part and reduces robustness of the overall system. Furthermore the production of two boards plus the additional connectors lead to higher costs of the overall system. We decided to place all components on one board, including the battery connector. All components are placed on one side, while the battery holder is placed on the other side. Placement of all components on one side also allows us to save one production day, an important factor for us as the production timeline was very tight. This way we were also able to place the battery holder in a way so that replacing the battery could be done by a untrained user.

Power supply. For power supply we opt for a standard lithium coin cell because we want to be able to buy the battery everywhere in the world, including the conference venue. To keep the overall node outline small, but still have enough energy capacity for a flexible use of the uParts - at this point the applications where not developed completely - we chose a 16 mm coin cell type battery. Such battery types also allow us to have a slightly higher peak power consumption, an important factor for selecting longer transmission ranges – than smaller size batteries.

We decided to not have an additional power regulation – e.g. power-up regulation – on board. Although it would be possible to drain slightly more energy from the battery the effort in additional part count and complexity of the hardware design was not seen as gainful. The reason is, that for low-duty cycle operation the additional energy that has to be spent for the voltage conversion is higher than the gain from being able to drain the battery more. The additional value of a stabilized power supply was not seen as all parts were able to operate within the intended voltage range - without reduced functionality.

Network: Transmission power design. One of the most important design decisions was the selection of transmission range and power. The main venue sites floor space was about 3000 m², so we decided to have a minimum coverage of 400 m² for each node inside the room and 200 m² for nodes that stand on the wall. We assumed that due to installation issues we had to install our equipment on the walls, which means that each router or access point can cover 200 m² resulting in a need for 15 infrastructure devices. Figure 3 gives an overview of the power consumption of the uPart design under various conditions (operating temperature 23 °C, RF frequency 315 to 433 MHz, Vdd = 3 V).

This decision was largely influenced by the fact the concrete conditions for the application settings were unknown. The used frequency was a Japanese ISM band, a frequency band that is also used by many other electronic devices as wireless microphones, wireless surveillance cameras or remote controls. This may lead to an increase of transmission error rate while reducing communication range. Because also the characteristic of possible disturbance (e.g. high level peaks, continuous high noise level) was unknown we were not able to address this issue in the design of the network protocol or hardware. To make sure that at least some information is transmitted even in worst case we decided for a rather high transmission power of 2dBm (at TX pin) with a maximum transmission range inside of about 30 meters (figure 3). This ensures a minimum transmission range of about 10 meters when using a bended whip antenna in a badge as used in the conference. Due to the high negative antenna gain caused by this type of antenna (about -40 dB), radiation power and field strength for the appliance (uPart in a badge with bended whip antenna) complies to the strict Japanese regulation rules (500uV/m at 3 meter distance).

The disadvantage of this approach is the high peak power consumption when sending (about 21mW). Although energy consumption was still much lower than with other types sensor network nodes for 2dB transmission power, the used battery types for the demonstration application were not specified for such a high power consumption. Using batteries out of specification normally results in bad battery performance: only a small fraction of the nominal energy of the battery can then be used. We worked around that problem by deliberately inserting (almost) no power consumption phases (0.8uA, see fig.3) after each sending phase to allow the battery to recover before the next power consumption time (figure 4). In our case, if we want to retrieve about 50 percent of the battery capacity (type CR1632), a sleeping period of over 36 seconds is required (assumption: sensor reading every sending cycle, 20°C temperature). This time may be reduced if transmission power is reduced. In figure 5 we summarized our measurements on minimal sleeping time in relation to RF output power. As shown the time for sensor reading is negligible, sleeping time is the dominating factor for the data sending interval.

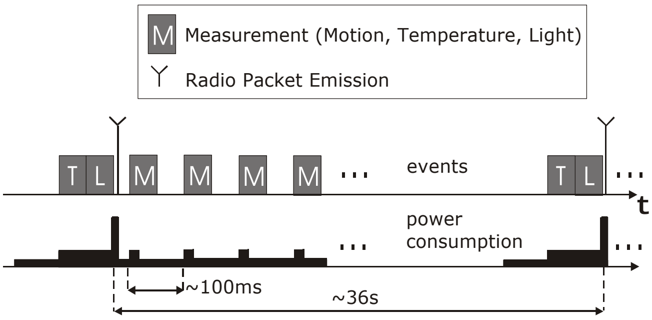

Figure 4. Current consumption of the uPart while sensing/sending/sleeping (timings for default configuration)

Transmission speed. Transmission speed was constrained by transmitter hardware used for the uPart. The transmitter allows a maximum transmission speed of 38.4 kbit/s, but using this speed leads to reduced transmission range of a few meters. To allow mid-range sending ranges (several 10 meters to 100 meter in-house) 19.2 kbit/s was selected as transmission speed (modulation: 2FSK). Because of lack of a receiver in the uPart design, communication was restricted to unslotted ALOHA. Unslotted ALOHA leads to a high collision rate when many nodes in range are trying to access the communication channel at the same time.

RECOMMENDED MIN SLEEPING TIME (SEC)	RF OUPUT POWER (SENSORS SWITCHED ON), 20°C; MAX RANGE INSIDE/OUTSIDE (19.2KBIT/S)
0.5	Output Power=-70 dBm, switched off sensors; 2/5 meter
2	Output Pow. = -70 dBm; 2/5 meter
4	Output Power = -12 dBm; 10/30 meter
9	Output Power = -4 dBm, 20/60 meter
36	Output Power = 2 dBm, 30/100 meter

Figure 5. Recommended sleeping time depending on communication range with CR1630 using a lithium battery

We expected around 100-150 nodes in one transmission cell in worst case, and less than 75 nodes in one cell in average. This leads to a maximum collision rate of around 20% and a average collision rate of around 10% which we seen as acceptable for our intended application (analytical results, best case, based on packet size as used in the demo application (400 bits including preamble), data-rate 19.2 kbit/s).

Network infrastructure. Information sent by the uParts is consumed by applications running on Internet-Protocol enabled devices (figure 6). Therefore, all uPart sensor information has to be forwarded to a backbone IP network. This is carried out by installing an access point infrastructure. As access points require cabling we were not sure if we are allowed to install them in all places of the conference site. To still obtain full coverage we developed an overlay network with so-called uPart Routers. These battery operated devices forward the uPart information to the next available Access-Point. To simplify debugging of the system routers use the same protocol and behave exactly like uParts.

To provide a robust setting for the uPart-Router overlay network we selected two simple approaches for routing: Fixed routing (route is entered into the router by DIP-Switch configuration) and a Flooding/MPR based routing approach. Simplicity of the approaches allows us to detect problems with the overlay routing quickly which we have seen as more important than high performance of the routing approach. The implementation of two routing methods gave us the flexibility to decide on the routing method depending on the situation.

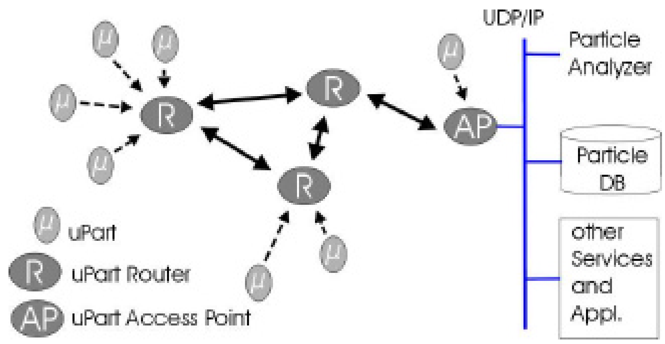

Figure 6. uPart Infrastructure

No extensive evaluation is carried out for this part of the system so far. Preliminary results with 160 nodes in coverage of a routing chain, a 3 hop chain of routers showed a throughput of ca. 60% (minimum) to 80% (average) for fixed route routing and about 60% for flooding (36 seconds sending cycle for each node).

Communication Layers. The lower communication layer (RF, MAC, Link) are designed especially according to the above mentioned requirements. To allow the reuse of and compatibility with existing software the highest layer of the ConCom [1] stack is reused. This allows us to use user programs, debugging and development tools and services developed for the Particle system. This decision largely reduces the development time for software. Location information was added by infrastructure devices on the ConCom layer; granularity of the location information was the cell of the incoming infrastructure device, e.g. the access point.

5. APPLICATIONS

Firmware. For the firmware of the uPart we had to decide between two option. Option 1 would be a specific application for the demonstration we had in mind. The advantage of this option is that it would be possible to integrate sophisticated activity recognition by implementing sensor-specific algorithms. Another advantage could be, that a very reduced set of information – e.g. only the activity changes detected – have to be transferred. This would save transmission time and energy.

A second option is the implementation of a generic program that continuously reads the sensor and – after simple processing – sends out this information over the network to services and applications. The advantage of this approach is the high flexibility: Many different applications can make use of the information sent by the uPart sensor node. We decided to implement the second option, as we did not know precisely what future applications should be supported by the uPart sensor system at design time of the demonstration. This approach also opens the system for use by others, e.g. other demonstrations while the conference.

The firmware was constructed as a continuous sensor loop reading where all the sensors with the exception of the movement sensor were read. The cycle of the loop was an adjustable parameter starting from 288 Milliseconds up to 78 minutes. We decided to send out sensor information via RF immediately after reading. Between sensor readings and communication the system was put into sleep mode (sensors, RF, CPU, other circuits switched off, WDT switched on). A complete reading and sending cycle takes about 30 Milliseconds.

The movement sensor was read out in a shorter cycle of 144 Milliseconds (see figure 4). This was needed to enabled more fine grained activity recognition. We did not use an interrupt driven detection of movement as experiments shown that this leads to an always on state of the system for high activity periods. In this situation battery was drained very fast because there was not enough sleep time left for recovering from high power consumption while the sending phase. In some cases - when used by jumpily users - a CR16xx battery was drained after 1 or several hours which we had seen as unacceptable for our application.

To allow sensing of activities in areas with no network coverage we implemented storing past sensor readings in an array. This array was sent every time sensor readings were sent. To save space in the packet and to allow to bridge longer times of disconnection this parameter could contain sensor readings in a compressed format. This compression factor was configurable by the user.

Configuration. To keep usage of uParts flexible and let the user decide on the parameters of monitoring, we liked to give the user the ability to re-configure the uParts during operation.Reconfiguration enables the user to set the monitoring parameters as sensor reading cycle, compression values and what values should be transferred in the past-sensor vector to her own needs.

To enable configuration, an input channel to the uParts was necessary. The radio of the uParts is only a transmitter, therefore it is not possible to use it for configuration means. Another option would be the use of an connector to connect a uPart to a USB or similar port on a PCs. Using an additional connector on the uPart has several drawbacks: It increases the cost and the user would have to install a certain software to do a reconfiguration of the uParts. To avoid the costs and complexity of using an extra software including e.g. USB-drivers, we decided to use the sensors on the uParts as the input channel.

We solved the configuration problem by (mis)using the light sensor as a receiving data channel to configure the uPart. A certain light modulation pattern was recognized by the uPart software as a configuration signal and used to change internal uPart settings.

Reception of information is triggered by switching on the uPart – i.e. when a battery is placed in the battery holder. After booting, the uPart first checks its light channel to find a configuration command and reads it. The light pattern can be produced by any controllable light source such as light bulbs, LEDs or computer screens. For convenience of the user we selected a LCD as a standard light source for such reconfiguring. We generate the light pattern with a Java-applet for web-browsers to achieve a very simple and wide-spread means for reconfiguring uParts. In practice, a uPart has to be positioned in front of a PC monitor or laptop screen, and then the java-applet on our website (see http://particle.teco.edu/upart/) can be used to reconfigure the uPart (Figure 6).

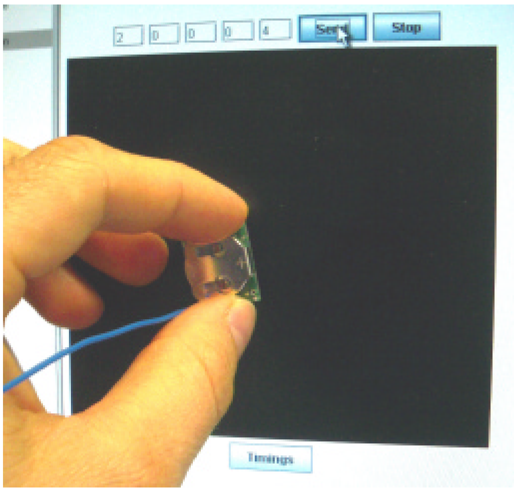

Figure 7. uPart configuration using a PC monitor

This approach also gives us the possibility for simple reconfiguration of uParts after the production for last minute adaptation of the demonstration system.

User Applications. Two Application were implemented by us, both of them allowing users to access their sensor / behavior data via either a terminal or a Web/Java application. Access to personal information was done entering the ID of the uPart into the application. We deliberately did not allow access to data via names or linking of names to ID to protect privacy of the users..

PROPERTY	**DECISION**
Attachment	In Conference Badge
Timespan	Mon-Wed.
Sensors: Movement	Ball switch, mid sensitive
Sensors: Light	Inhouse Sensitivity, wide angle
Sensors: Temperature	Simple, fast start-up
Battery	Lithium Coin Cell
Board	Single board
Coverage	Main Conference (plus Buffer of sensor readings)
Communication	Simple, long transmission range, unslotted ALOHA, 19.2 kbit/s, wire antenna
Routing	Simple fixed, flooding
Firmware	Generic, long cycle sensor reading (36 sec), past-sensor reading buffer
Applications	Configuration, Activity graphs, sensor graphs

Figure 8. Properties and decisions made while the design process of the uPart demo device and application

6. EXPERIENCE

Setup of the hardware was done ad-hoc on the conference site without any major problem. Attendees of the Ubicomp conference where asked if they would like to have a uPart to carry it in their badge at registration time. Almost all conference participants agreed to wear a uPart, at the end we gave out over 500 uParts to the total 625 attendees (625 attendees includes press and other 1-day attendees).

Privacy was no concern with our uPart system. The application was build to be anonymous, only attendees know the number of their uParts. Although we are aware that this does not completely protect privacy - theoretically behavior was observable and conclusion may be drawn even from the anonymous set of data to assign the behavior to the person - this was not seen as no major problem for attendees at the end.

We experienced that some of the participants were first reluctant to take part in the experiment and refused to take a uPart. They then first checked what information where handled and detected by the uPart system by asking colleagues already using the system, to finally come back at a later point in time the ask for their uPart.

The following sections will shortly discuss decisions made when designing the uPart demonstration device and application (see figure 8) in the light of the Ubicomp 2005 demonstration.

6.1 Applications, Attachment, Timespan and Use

User accessed their profile for their uPart using the terminal standing next to our demonstration booth or via their own laptop 1847 times. During coffee and lunch breaks and during demo and poster sessions the terminal was almost continuously occupied by several attendees retrieving their uPart information using our application software to see their activity and sensor information (figure 9). Compressed data where seen as very useful for bridging times of disconnection as lunch time.

Attachment of the uPart in the badge was not found as any problem for the setting. We initially feared that e.g. the wire antenna was seen as problematic for users as the antenna could cover part of the name on the badge. We found instead of being annoyed many participants took the opportunity to make the wire antenna a medium for creating an own expressing by folding the antenna in special ways – e.g. in form of a flower or a knot. Time span for the run of the uPart system was appropriate as there was only IP network access – needed to see any data – between Monday and Wednesday.

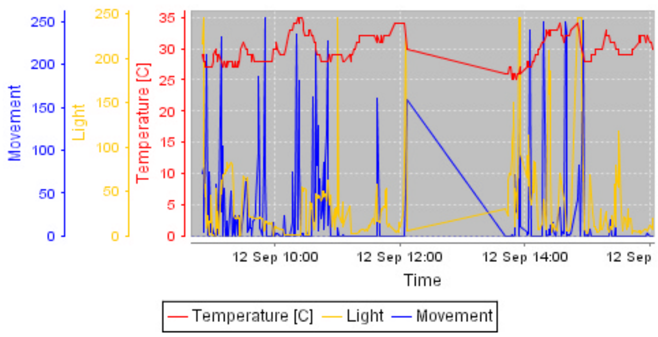

Figure 9. User application showing sensor and activity information (buffer values: temperature, movement)

6.2 Firmware

The generic software approach was found useful for the general development of third party software. Due to the very open approach of our system other research groups were able to write applications using the data from our uPart demonstration system. For example, the Hide Tokuda Laboratory at Keio University was able to write an application using the data from our uPart demonstration system and to integrate this in their Tokuda Lab's Smart Furniture system that was demonstrated while the conference. The application uses activity and number of people in one of the conference demo rooms and generates an interactive graphic from it. The application was programmed in one day

The sensor buffer with a compressed array of 24 past sensor values was found very useful for our application setting. It especially helped us to cover the time span of the lunch as there was no network connection at the lunch place. Although the values were much more coarse grained (see figure 9, readings between 12:00 and 13:30) there was still enough valuable information left for detecting at least some activities.

6.3 Communication

Communication range of the uParts was between 15 and 30 meters depending on room conditions and the number of people and other obstacles standing between the infrastructure device and the uPart. Due to the use of the buffer for past sensor readings, partial coverage of the conference area was enough to retrieve activity information.

Total packet loss was quite low (around 80% in first evaluations). As communication speed goes with the network access time for sending, this is also an indication that the choose communication speed was high enough for the application area. We used fixed route routing to avoid any packet overhead. The dip-switch configuration of the routing was found as very convenient and very fast to set-up. Initial evaluations showed that packet loss was in the range of the measurements taken in our laboratory (see above).

6.4 Hardware

Board. We encountered two hardware failure of the uParts during the conference. Overall, mechanical and electrical robustness of the sensor nodes was above expectation.

Battery. The runtime of the uPart with the Lithium coin cell was much beyond initial expectation and analytical computation. In total the runtime with the conference configuration was between 3-4 month. We could therefore easily used a higher duty cycle (more sensor readings and more often communication) without consuming up the whole battery while the conference. A higher duty cycle would have given us the opportunity for more fine grained activity detection but also may had lead to higher collision rates due to more network utilization in very dense settings as our conference event.

Sensors: Movement. The movement sensor was the most interesting one for the attendees to see their activities while the conference. With the help of the sensor phases of low activity – while in the plenary session, while sleeping the session, while waking around , etc. – could be clearly separated. A more fine grained evaluation of this information is ongoing.

Sensors: Light. Light data was intended to show conditions as inside/outside. A problem with the light sensor is, that it is unclear if the uPart is worn in the front side of the badge or in the back side of the badge. In practice, the badge often turns, so that mostly the uPart was worn under both conditions. The problem was partially overcome by the wide sensitivity angle of the used light sensor. It helped us to detect light conditions independent of the sensor nodes state (frontside/backside). The sensor was never saturated inside a building, but under all conditions saturated outside the building in daytime - even if worn on the back side of the badge. We found that using the light sensor readings an application was able to separate inside and outside not only by the light level but also by evaluating the change in the light level. A regular change in the light level with the same Minimum and Maximum clearly indicates an artificial light situation (flickering lights). With the help of the light level we were also able to separate plenary sessions (dimmed light) and other artificial light situations.

Sensors: Temperature. Temperature was an indication if the sensor was worn towards the body (back side of the badge) or away from the body. This is of help for application to interpret the light sensor values better. Only when sensors are worn away from the body, a temperature measurement could be used as recognizing environment conditions.

Conclusion. While the design of our system we found, phrased and rephrased several design criteria that guided us. From a retrospective analysis of our design criteria, we come to the conclusion that at the end of the design process we finally selected the option with the lowest complexity, but fits our minimal needs in every design decision. This often means that optional features that we liked to see in the system at the beginning are not included in the final system design anymore. We found, that this restriction did not have negative implications for the overall application at the end. Rather than delaying or hindering the process of developing applications and functionality on top of the simple system the uPart system design seems to enable and accelerate the implementation of applications. We believe this is due to the clear focused functionality of the overall system and a result of the minimal system design that also leads to a minimal interface design.

One conclusion is that low complexity and minimal functionality can be seen as an ultimate meta-design criteria covering all other (more technical) design criteria. As a rule: ***The option with the lowest complexity that fits the minimal needs for the system is the most appropriate***. We are convinced that using this rule instead of the various design criteria may lead to simplified and clearer design process in the future. In our case, the low complexity reduces cost of production, cost of software, increases robustness, is normally the most standard option and often provides the most simple and smallest physical outline solution. It also largely reduces time to develop and produce the system.

7. RELATED WORK

Taking a closer look into the typical use of the above mentioned sensor network in nowadays, activity recognition and ambient intelligence [3] are the major use cases of sensor networks for indoor settings. The use of many sensors of low complexity was earlier identified to be useful for activity recognition [4]. Outdoor settings mostly focus on large area coverage with multi-hop communication. An example for a large scale sensor network monitoring agriculture can be found in [5]. For both fields of application, it is of high interest to increase the number of independent sensors above a critical number. The authors of [6] could track people and recognize their activity using very simple sensors that only distinguish between binary values such as "moving" and "resting". They concluded that the algorithms would work more robust and accurate once the number of sensors is significantly increased. This aspect of research using dense settings of sensor networks promotes a *new and alternative system design* of a sensor network, that focuses more on these requirements and reflects the experiences researchers have collected with existing sensor networks. There has also been a large scale experiment on a conference using motes [7]. This experiment is similar to ours but it uses more complex standard hardware.

Our setting is also close to conference badge systems, e.g. from Interrelativity (interrelativity.com, a preliminary version of the system was shown at Ubicomp 2004). Theses systems differ from our approach in that these systems focus on one special application domains (e.g. social relation to other attendees) and are based on RFID technology. In contrast to this, our system does not provide a concrete application but is intended to be an enabling technology providing location but also other sensor information to such applications. Also in contrast to these systems our approach does not require identification of participants.

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