Progress report:

Implicit situation awareness of a wireless sensor network utilising channel quality estimations

August 16, 2011

Stephan Sigg

National Institute of Informatics (NII)

Information Systems Architecture Science Research Division

2-1-2 Hitotsubashi
Chiyoda-ku
101-8430 Tokyo
Japan

Abstract

This document summarises current achievements and progress in the project 'Implicit situation awareness of a wireless sensor network utilising channel quality estimations'. The report is structured in four logical parts. The first part covers the progress during the first two months of the project until the end of January 2011. In the second part we cover research progress until the end of July 2011. The third part covers the open research topics and research plans for the upcoming five months of the project year. Additionally, a concluding chapter details further cooperation during the project that is not directly related to the project proposal.

1 Progress report: December 2010 until January 2011

The research on the DAAD-FIT project 'Implicit situation awareness of a wireless sensor network utilising channel quality estimations' was officially started in December 2010. Preliminary studies were undertaken since about autumn 2010. Currently an extension of the project for one additional year was accepted. The work packages are addressed in this document according to the following notation.

First year of the research project (December 2010 until November 2011

PJ1–WP1 Context classification based on channel quality measurements

PJ1–WP2 Experimental measurements of context related channel qualities

PJ1–WP3 Context prediction

PJ1–WP4 Installation and evaluation

Tasks	Dec - Feb	Mar - May	Jun - Aug	Sep - Nov	
PJ1–WP1					**2.4**
WP1.1	0.6	0.4			*1.0*
WP1.2	0.4	0.2			*0.6*
WP1.3		0.4	0.4		*0.8*
PJ1–WP2			0.6		**0.6**
PJ1–WP3				0.6	**0.6**
PJ1–WP4				0.4	**0.4**
Sum	1.0	1.0	1.0	1.0	**4.0**

Second year of the research project (December 2011 until November 2012

PJ2–WP1 In-network context processing

PJ2–WP2 Ad-hoc secure communication

PJ2–WP3 Instrumentation and case studies

Tasks	Dec - Feb	Mar - May	Jun - Aug	Sep - Nov	
PJ2–WP1					**2.0**
WP1.1	0.5	0.2			*0.7*
WP1.2	0.5	0.5			*1.0*
WP1.3			0.3		*0.3*
PJ2–WP2					**1.4**
WP2.1			0.5		*0.5*
WP2.2			0.2	0.4	*0.6*
WP2.3				0.3	*0.3*
PJ2–WP3					**0.6**
WP3.1		0.3			*0.3*
WP3.2				0.3	*0.3*
Sum	1.0	1.0	1.0	1.0	**4.0**

The first work package in this project is focused on context classification based on channel measurements. We proposed to utilise channel measurements as input to a graph-based in-network context classification.

In Work package 1.1, which is scheduled for the first six months of the overall project duration, this algorithm is developed together with an approach to identify communication links between nodes in this in-network processing which are pareto optimal regarding the distribution of computation and communication load.

Until the end of January 2011, we have conducted studies related to the utilisation of channel measurements for the classification of situations, developed a vector-based context representation that enables arbitrary composition of sub-computations in a network of distributed nodes, studied the use of prediction methods in order to identify the nodes in the network that should contribute to a distributed computation and finally studied an unobtrusive mechanism to establish a secure channel among devices in an ad-hoc manner based on ambient audio.

The last aspect provides already preliminary results for the second project phase.

1.1 Vector-based representation of situation classifications

(PJ1–WP1)

We considered alternative representations of situational context which are well suited in order to allow the aggregation of partial representations of context classifications in arbitrary order.

We proposed a vector based representation of context in which the rotation of a vector represents the current measurement value. Distinct types (e.g. light intensity, humidity, temperature) are represented by multiples of unique rotations of a vector. The rotations that represent distinct feature classes are required to be no multiple of each other and no multiple of a full rotation so that, after combining rotations of distinct vectors, the resulting rotation still uniquely represents a valid and unique representation of the combined measurements. Figure 1 illustrates this concept.

This representation already enables a distributed aggregation of measurements in a network. The order in which rotations are applied can be arbitrary and combination of only a subset of vectors represents a partial computation that can be combined with partial computation of other parts of the network. This approach was published in [10].

Building on this development we will consider additional operations for combining vectors and additional information contained. For instance, the length of a vector could represent a confidence value on the (combined) measurement which would necessitate a more advanced operation for vector combination.

This vector-rotation-based representation constitutes an approach to solve WP1.1 which does not require an optimum structure for the communication links among nodes as originally proposed for WP1.2. Instead of deriving an optimum graph-structure over a network of wireless nodes, this vector-representation allows for the aggregation of context data (vectors) in arbitrary order. Hence, the underlying graph-structure and processing order is irrelevant in this case. Although

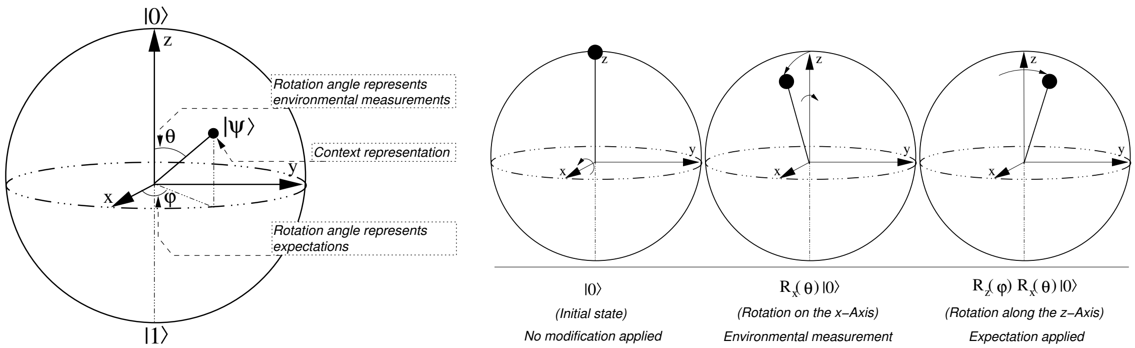


Figure 1: Representation of a situation representation on a sphere and applications of rotations to a vector

Table 1: Accuracy of the implicit situation awareness.

Situation	mean	median	σ
Door state (opened/closed)	0.952	0.9513	0.0099
Presence of individual	0.817	0.8238	0.0455
Phone call (gsm)	0.9	1.0	0.32
Door opened (condition: Empty room)	1.0	1.0	0.0
Door closed (condition: Empty room)	1.0	1.0	0.0
Door closed (condition: Room occupied)	0.832	0.83	0.041
Door opened (condition: Room occupied)	0.976	0.98	0.0184
Room occupied (condition: Door closed)	0.673	0.66	0.1143
Room occupied (condition: Door open)	0.595	0.54	0.1247
Empty room (condition: Door closed)	1.0	1.0	0.0
Empty room (condition: Door open)	1.0	1.0	0.0

this solution already solves the algorithmic part of WP1.1, we will later also consider a graph-based approach and compare both approaches and then also address the related workpackages WP1.2 and WP1.3.

1.2 Situation awareness based on channel measurements

(PJ1–WP2)

We conducted studies on the general feasibility of classifying situations based on channel measurements. In these preliminary studies we utilised centralised context processing algorithms. In particular, with the help of software defined radios[1], channel fluctuations could be visualised and analysed. We considered the noise figure, the signal amplitude, the frequency and variance of amplitude changes over a fixed time window and the energy on predefined frequency bands as features for situation classification. With these features we have been able to detect ongoing phone calls, presence of individuals and movement in a room. Furthermore, we could state estimations on the position of people in a room, the person count and also detect simple activities such as walking, sitting or standing. These results show that situation awareness based on channel measurements is feasible indeed [6, 12]. Table 1 exemplary depicts some of our results for the three distinct situations of an opened or closed door, a moving person or an ongoing phone call. A paper with additional studies on this topic was presented at the CAPS 2011 conference [7].

These experiments demonstrate the general feasibility of utilising RF-channel measurements to derive context classifications. These are the first publications in this direction and we consider the success-rates and diversity of classification as sufficient to achieve basic recognition

[1] http://www.ettus.com

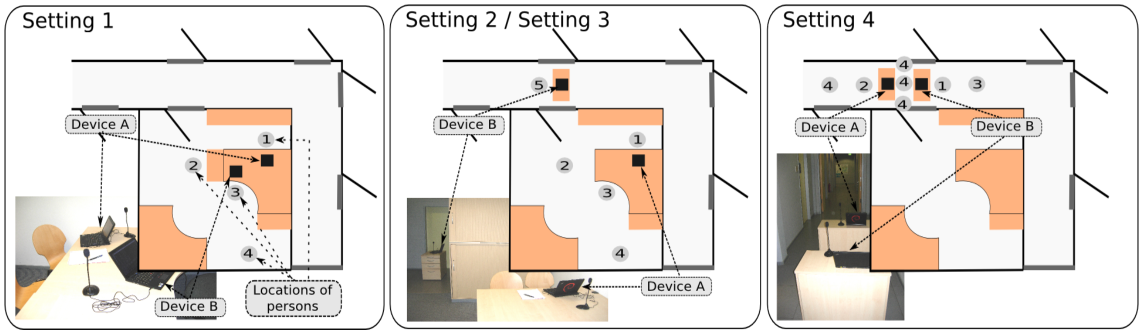


Figure 2: Schematic illustration of the four settings utilised for the case study.

tasks. Further experiments have been conducted also to increase the data footage in additional situations (cf section 3.2). These results complete WP2 of the project proposal.

1.3 Prediction to identify nodes that participate in a computation

(PJ1–WP3)

Also, possible uses of prediction have been considered. In a Work-in-Progress paper accepted at PerCom 2011 [4] we considered the possibility to use context prediction in order to activate or deactivate sensors based on their predicted usefulness. This will reduce the energy consumption and can also help to identify the nodes that should span the context recognition system in our approach. Generally, this work is related to PJ1–WP3. The adaptation to the graph-based algorithm remains as an open task for this work package.

2 Progress report: February 2011 until July 2011

Since February 2011 I attended the KiVS 2011 conference and the Pervasive 2011 conference as well as the adjunct IWSSISPMU 2011 workshop on spontaneous secure mobile device interaction. Also, I co-organised the CoSDEO 2011 workshop in Como, Italy. These events - especially the CoSDEO Workshop and the IWSSISPMU workshop featured several presentations relevant to the research project. On the IWSSISPMU workshop I had the chance to obtain a better insight into research conducted on context-based security. Since the workshop was very discussion-intensive, all participants also used this opportunity to consider new collaborations and discuss the different solutions taken by various researchers. The topics on the CoSDEO workshop were more diverse and generally connected to context computing. Several opportunities for collaboration however, also evolved from the discussions with workshop participants.

2.1 Secure ad-hoc device authentication based on environmental context

(PJ2–WP2)

We conducted several studies on the possibility to utilise context information in order to establish a secure channel among nodes in close proximity without the requirement of any additional input data. A first study on this method was submitted to Mobisys 2011 at December 11, 2010.[2] Figure 2 depicts the scenarios we utilised in this case study and table 2 shows the success probability in the various scenarios.

A revised study comprising three additional experimental settings, a more detailed analytical discussion and also an estimation on the entropy of context patterns derived was submitted to IEEE transactions on mobile computing [14]. We propose to establish a secure communication channel among devices based on similar audio patterns. Features from ambient audio are used

[2]This submission was rejected. Although the work was considered as promising generally, two of three reviewers demanded additional experimental studies in varying environments.

Scenario	1	2	3	4
Successful attempts	0.9	0.4	0.0	0.8
Bit errors corrected ($\varnothing$)	179.6	170.75	–	173.75

Table 2: Observed probability of correct synchronisation in the four scenarios considered

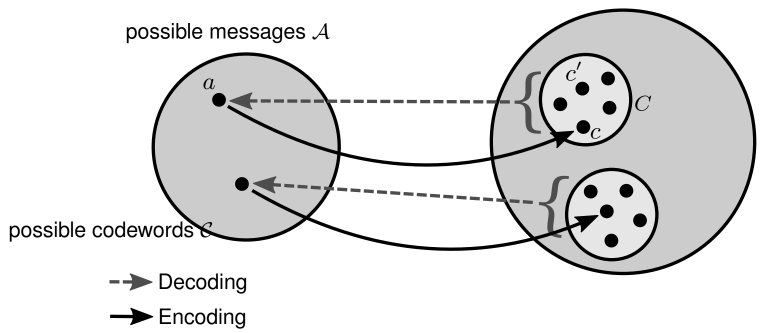


Figure 3: Encoding maps message $a \in \mathcal{A}$ to codeword $c \in \mathcal{C}$. Decoding maps several $\tilde{c} \in C, C = \{c, c', c'', \ldots\}$ to one $a \in \mathcal{A}$

to generate a shared cryptographic key between devices without exchanging information about the ambient audio itself or the features utilised for the generation process. We explore a common audio-fingerprinting approach and account for the noise in the derived fingerprints by employing error correcting codes. Also, the computational complexity of the approach is derived. This fuzzy cryptography scheme enables the adaptation of a specific value for the tolerated noise among fingerprints based on environmental conditions by altering the parameters of the error correction and the length of the audio samples utilised. This scheme for context-based device authentication was generalised in [15] (cf. section 3.1; Figure 6 illustrates the general modules for the encryption scheme.).

In [14] we experimentally verify the feasibility of the protocol in four different realistic settings and a laboratory experiment. The case studies include an office setting, a scenario where an attacker is capable of reproducing parts of the audio context, a setting near a traffic loaded road and a crowded canteen environment. We apply statistical tests to show that the entropy of fingerprints based on ambient audio is high. The proposed scheme constitutes a totally unobtrusive but cryptographically strong security mechanism based on contextual information. The python-instrumentation was made public through an open-source license.[3] Figure 3 depicts the encryption scheme. **(PJ2–WP3)**

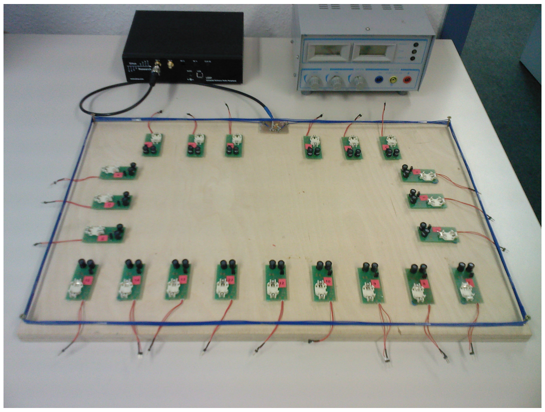
Building on these results, in [13] we study the entropy of audio fingerprints which can be utilised to pair devices in close proximity. In this work, for 600 audio fingerprints from 5 distinct audio classes recorded at 3 different locations, we applied 7490 statistical tests from the dieHarder battery of statistical tests. According to the statistical tests applied, we could not find any BIAS for the ambient audio-based fingerprints. The results of this study are available online.[4]

In [9] we discuss the use of context for cryptographic applications and present a case study in which we exemplary utilise ambient audio to establish a common cryptographic key among devices in proximity. We show that we can tweak the security level of the application by adapting the parameters of the Reed-Solomon error correcting code utilised.

Overall, these studies complete PJ2–WP2.2 and PJ2–WP2.3 as well as PJ2–WP3.2 for the instrumentation of the secure communication scheme. Regarding PJ2–WP2, we will in the upcoming months also consider other environmental context features as stated in PJ2–WP2.1.

[3] The installation can be accessed through the public GIT-repository https://gitorious.org/fuzzy-pairing

[4] All results are available at http://www.ibr.cs.tu-bs.de/users/sigg/StatisticalTests/TestsFingerprints_110601.tar.gz



(a) The experimental setup consists of 21 transducers and one receiver connected to a PC

		Binary Query	Proportion Query	
Setting	**Number of Trials**	**Correctly identified Msg.**	**Average Error Sum**	**Average Error Mean p. Class**
21	10	88,57%	12,38%	1,77%
18,3	10	89,05%	11,90%	1,70%
15,6	10	91,90%	8,57%	1,22%
12,9	10	97,62%	2,38%	0,34%
15,3,3	10	90,00%	10,95%	1,56%
12,6,3	10	89,05%	11,43%	1,63%
9,9,3	10	89,05%	10,95%	1,56%
9,6,6	10	82,38%	17,62%	2,52%
12,3,3,3	10	82,86%	17,62%	2,52%
9,6,3,3	10	82,38%	17,14%	2,45%
6,6,6,3	10	80,95%	18,10%	2,59%
9,3,3,3,3	10	80,00%	21,90%	3,13%
6,6,3,3,3	10	85,71%	14,76%	2,11%
6,3,3,3,3,3	10	80,00%	20,95%	2,99%
3,3,3,3,3,3,3	10	79,52%	19,52%	2,79%

(b) Experimental results

Figure 4: Experimental setup and results for our case study on in-network processing

2.2 In network processing

(PJ2–WP1)

The in-network processing part of the project proposal was brought forward in a collaboration with colleagues from TecO at the Karlsruhe Institute of Technology (KIT).

We generally considered encoding of data sequences that allow with a high probability to identify individual sequences from an unsynchronised superimposition of a high number of physical signals at a remote receiver. The submission was rewarded with the best paper award at the 7th International Conference on Intelligent environments [5]. We consider in-network processing in intelligent environments which are currently implemented with standard wireless sensor network technologies using conventional connection-based communications. Since, however, connection-based communications may impede progress towards intelligent environment scenarios involving high mobility or massive amounts of sensor nodes, we present a novel approach based on collective transmission for item level tagging using printed organic electronics, which implements robust, collective, approximate read-out of large numbers of simple tags. Figure 2.2 depicts the experimental setup and results achieved. Our approach uses mechanisms for calculation by simultaneous transmission. We detail the collective transmission approach, discuss its implementation in the organic printed label scenario, and show first results of experiments conducted with our smart label test bed.

This study contributes to our attempt to state an improved method for network coding as detailed in PJ2–WP1.1.

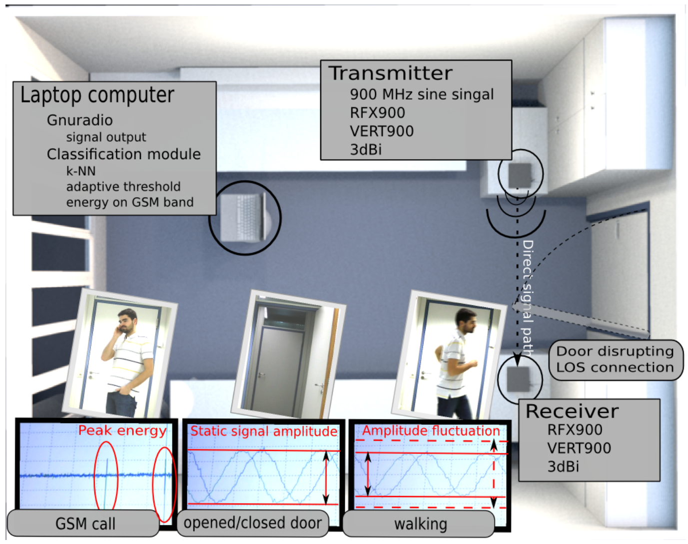
2.3 Implicit situation awareness

(PJ1–WP1)
(PJ1–WP2)

In order to demonstrate that situation awareness is possible based on the RF-channel, I conducted a case study together with members from TU Braunschweig, the TecO at the Karlsruhe Institute of Technology and the National Institute of Informatics in Tokyo. First results were presented as a video at the Pervasive 2011 conference [8]. We demonstrate a system for activity recognition based on features extracted from the RF channel. In particular, we show how static changes in the environment such as moved furniture, activity of a person and an ongoing phone call are detected based on RF channel measurements. Figure 5 depicts the experimental setting featured in the study and results on the classification accuracy. We are currently working on the recorded data from this case study and will publish further, more detailed results on the accuracy of context classification based on RF-channel features in the second half of 2011.

We utilised these results and the classification algorithms to demonstrate how an interactive beamforming protocol can be modified and improved by RF-channel aware nodes in [11]. We

(PJ1–WP1)
(PJ1–WP2)



(a) Schematic illustration of the recognition system

Situation	mean	median	σ
Door state (opened/closed)	0.952	0.9513	0.0099
Presence of individual	0.817	0.8238	0.0455
Phone call (gsm)	0.9	1.0	0.32

(b) Accuracy of the implicit situation awareness

Figure 5: Experimental setting, recognition algorithms utilised and experimental results

study distributed adaptive beamforming in networks of wireless nodes. In particular, we observe that for the synchronisation of carrier phases, distinct algorithmic configurations are optimal in various environmental settings and propose a protocol that utilises organic computing principles to find optimum parameters. Furthermore, we study the impact of different modulation schemes on the bit error rate of a signal sequence transmitted collaboratively by distributed devices via adaptive beamforming.

Overall, with several studies conducted which are related to PJ1–WP1.1 and PJ1–WP2, algorithms for RF-channel based situation awareness have been developed, discussed and verified in several case studies. To complete these workpackages, we will use the recorded data to provide a comprehensive study on features suitable for RF-channel-based situation awareness and the expected classification accuracy.

3 Research aims: August 2011 until November 2011

In the second half of the first project year, I will attend the Casemans Workshop of the Ubicomp 2011 conference and co-organise the 3rd CoSDEO workshop in conjunction with MobiQuitous 2011. Additionally, a workshop proposal for a workshop on context-based-security will be submitted to ARCS 2012. Also, from the open research questions identified for context-based device pairing so far, Prof. Yusheng Ji and I submitted a joint project proposal with University of Kassel (Chair for Communication Technology, Prof. Dr.-Ing Klaus David) to JSPS/DFG. The project will focus on an improved mechanism for context-based device authentication based on spectral flatness or spectrogram peaks as well as on a framework for fine-grained context based unobtrusive traversal between distinct security classes on mobile devices. Additionally, we will focus on additional context classes such as light and proximity. In particular, the project would extend the research questions stated for the second project year. All research questions considered are or-

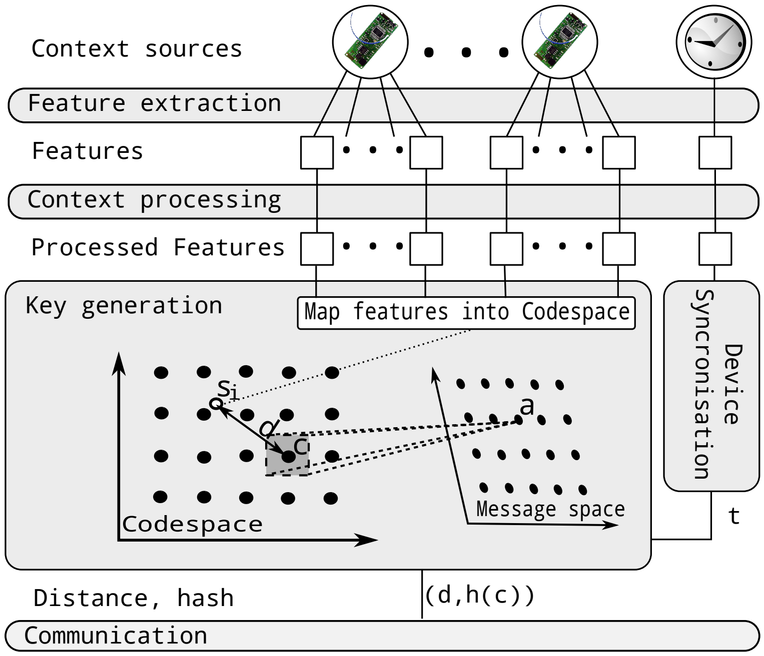


Figure 6: Modules in our framework for device-pairing based on arbitrary contextual information

thogonal to the ones detailed in this proposal. The research will be conducted by a JSPS-funded project researcher for the duration of one year. This will open further collaboration opportunities in the second project year.

3.1 Secure ad-hoc device authentication

(PJ2–WP2)
(PJ2–WP3)

We submitted a paper to MobiQuitous 2011 in which we present a framework for secure device pairing based on arbitrary context information [15]. The feasibility of the approach is exemplified utilising ambient audio. In contrast to related work, we utilise fuzzy cryptography schemes to establish a common secret among devices and to account for noise in the contextual features. The framework is implemented for ambient audio and its feasibility is demonstrated in a case study. Figure 6 gives a schematic overview on the modules proposed for the framework.

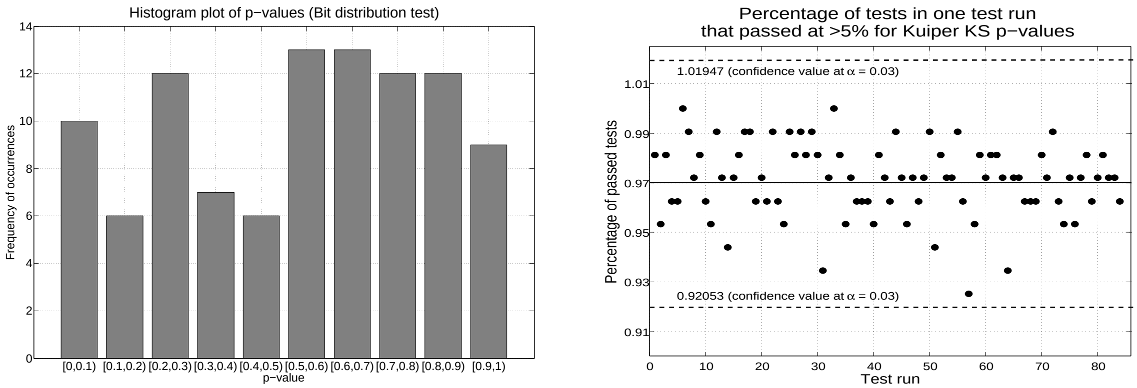
Additionally, we discuss properties of fingerprints from ambient audio and estimate the entropy of fingerprints in statistical tests. We could show that the entropy of the method is high so that an adversary can obtain only sparse information from a channel that is encrypted in this way (see figure 7). In the figure, the entropy of generated fingerprints is estimated by applying the dieHarder [1] set of statistical tests. This battery of tests calculates the p-value of a given random sequence with respect to several statistical tests. The p-value denotes the probability to obtain the provided input sequence given a truly random bit generator. We applied all 24 statistical tests in the set of fingerprints of 480 bits length. In 7490 test-batches of 100 repeated applications of one specific test each, only 173 batches, or about 2.31% resulted in a p-value of less than 0.05.[5] Each specific statistical test was repeated at least 70 times. The p-values are calculated according to the statistical test of Kuiper [2].

3.2 Implicit situation awareness

(PJ1–WP1)
(PJ2–WP2)

From our studies on implicit situation awareness (cf. section 2.3, we are currently reviewing and analysing the data obtained. Overall, more than 5GB worth of channel measurements from

[5]Results are available at http://www.ibr.cs.tu-bs.de/users/sigg/StatisticalTests/TestsFingerprints_110601.tar.gz



(a) Histogram plot of p-values for the RGB Bit Distribution test

(b) Proportion of sequences passing a test

Figure 7: P-values for statistical tests of the dieHarder battery of statistical tests

various test subjects conducting 5 activities in 15 distinct locations are reviewed. We consider the possibility to detect environmental conditions, presence and count of non-actively transmitting individuals, as well as their activity and status. Due to the high penetration of the RF sensor in common equipment, the additional cost for utilising this sensor in an application is considerably low. The application must simply utilise the information that is available but discarded unused in these devices. RF signals provide several properties that are of particular interest in emergency scenarios as, for instance, fire fighting. In particular, RF transmission is tolerant to

- Inaccurate or hasty placement of nodes regarding height, orientation or exact distance between nodes
- Non-line of sight connections
- Sight obstruction by, for instance, smoke, fire, toppled down objects or concrete as well as extinguishing foam
- Heat or cold

Our results will focus on activities from such an emergency situation. We are currently extracting features from the data and are conducting and improving classification in an off-line process.

3.3 In-network processing

(PJ2–WP1)

For the in-network processing we are currently considering recent studies conducted on an iterative feedback-based transmit beamforming approach (cf. [16] and references therein). In this approach, several transmit nodes align the phase of their carrier signal in a random search manner. We will show that it is feasible to build arbitrary neuron-like structures in a dense wireless sensor network with this approach. We applied biologically neuronal structures to establish a WSN emulating neuronal activities. Two different types of wireless nodes working together are used to mimic the behaviour of a neuron consisting of dendrites, soma and synapses. In this way we provided the fundamentals for neuronal networks in environments to emerge cognitive capabilities in spaces.

Generally, the transmit nodes in our beamforming protocol represent the dendrites that are activated by impulses from nearby synapses. Activated dendrites then achieve collaborative beamforming to transmit to their associated synapse. The benefit of this approach is, that it does not require time synchronisation since the beamforming transmission guarantees that the received signal strength of a transmission is spatially sharply focused on a specific synapse so

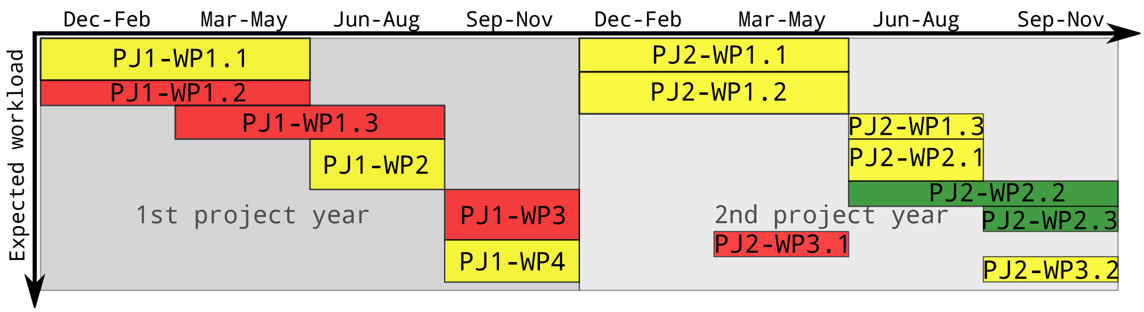


Figure 8: Completion of workpackages for both project years. Colour code: Green–Work package completed; Yellow–Considerable part of workload completed; Red–No significant progress or not started.

that the noise at other synapses is low. Data can then be transmitted simultaneously in various neighbouring and possibly in their structure interleaved 'neurons' over a wireless channel. Clearly, when we could succeed in designing a robust mechanism based on this approach that establishes an overlay of neurons from a wireless sensor network, arbitrary linear functions might in theory be solved by such a network design. If this approach were successful, it would solve work package PJ2–WP1. We consider to submit first results of this study to MobiQuitous 2011.

3.4 Summary of open research questions and future directions

Figure 8 depicts the completion status of workpackages for the current project year. For practical reasons the work packages have been addressed in different order than originally planned. The following sections detail open research questions for the respective workpackages.

3.4.1 PJ1–WP1: Context classification based on channel quality measurements

For PJ1–WP1.1, several solutions have been considered with the vector-based context representation [10] and a neural-network-overlay of a sensor network (cf. section 3.3). A graph based approach, as originally stated, was however not yet considered. It will be studied in the second half of 2011. Similarly, PJ1–WP1.2 and PJ1–WP1.3 are not addressed yet but will be studied until the end of 2011.

3.4.2 PJ1–WP2: Experimental measurement of related channel qualities

We have provided extensive studies on channel-based situation and context classification. A comprehensive study on suitable features and their accuracy for common activities is being prepared and will be submitted in the second half of 2011 (cf. section 3.2).

3.4.3 PJ1–WP3: Context prediction

This work package builds on PJ1–WP1. It will be addressed after the completion of PJ1–WP1 in the first half of 2012.

3.4.4 PJ1–WP4: Installation and evaluation

With the case studies on channel-based situation awareness and context classification (cf. section 3.2), this work package is generally completed. Results will be published in the second half of 2012.

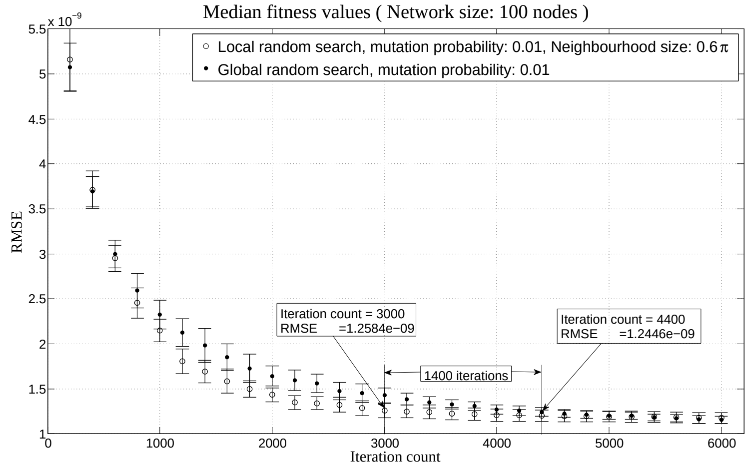


Figure 9: Performance of the local random search implementation

3.4.5 PJ2–WP1: In-network context processing

This work package will be finally completed by the studies described in section 3.3.

3.4.6 PJ2–WP2: Ad-hoc secure communication

A significant part of PJ2–WP2.1 is solved by [14, 15]. To complete the work package, we will improve the robustness of the fingerprinting approach and consider other context sources in 2012. The workpackages PJ2–WP2.2 and PJ2–WP2.3 are completed by the studies described in [9, 14].

3.4.7 PJ2–WP3: Instrumentation and case studies

The work on PJ2–WP3.1 which constitutes a USRP-based case study is not yet started. This work package will be addressed in 2012. Work package PJ2–WP3.2 is mainly completed by [9, 14]. The source code utilised is made public via a Git-Repository.[6] It will be ported to the android operating system in the second half of 2011.

4 Further research activities and cooperation

The following sections detail research conducted during the project duration that is only loosely connected to the topic of the project proposal.

4.1 Transmit collaboration in wireless sensor networks

In cooperation with Prof. Yusheng Ji we study in [16] a local random search method for closed-loop feedback based distributed adaptive transmit beamforming with neighbourhood size $\mathcal{N}$. Figure 9 depicts the performance of the algorithm with a neighbourhood size of $\mathcal{N} = 0.6\pi$ compared to a global random search approach ($\mathcal{N} = 2\pi$). We observe that the local random search method reaches lower RMSE values faster. In particular, the RMSE value reached by the local random search approach after 3000 iterations is achieved by the global random search method only after

[6] https://gitorious.org/fuzzy-pairing

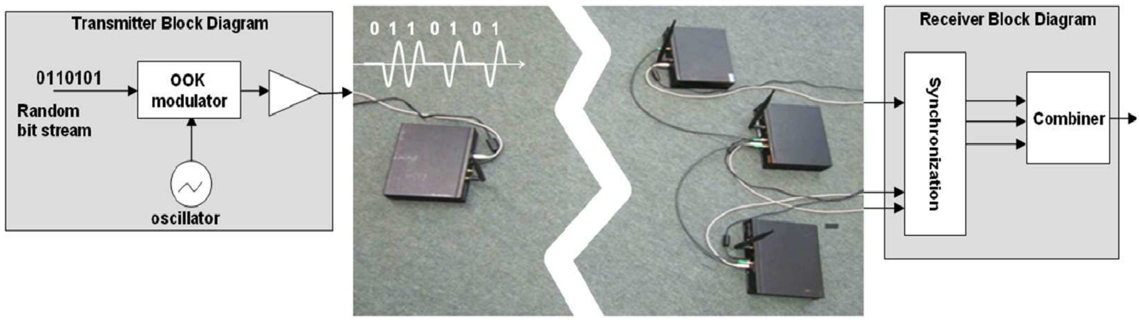


Figure 10: Illustration of the experimental setting for receive beamforming

about 4400 iterations. Due to noise, the synchronisation quality is not much improved afterwards so that the global random search eventually catches up.

We could derive an asymptotically sharp bound on the expected feedback-based carrier synchronisation time for distributed adaptive transmit beamforming among n nodes with k possible phase offsets of $E[T_{\mathcal{P}}] = \Theta\left(n \cdot \mathcal{N} \cdot \log(n) + \frac{\log(k)}{\mathcal{N}}\right)$. This bound is significantly lower than the previously known expected asymptotic synchronisation time for this feedback-based iterative carrier synchronisation. For the local random search method we derive the optimum neighbourhood size $\mathcal{N}$ with respect to the number of participating nodes and the count of physically possible carrier phases as $\mathcal{N} = \left\lceil \sqrt{\frac{\log(k)}{n \cdot \log(n)}} \right\rceil$. Also, we show that the algorithmic parameters for the synchronisation are impacted by environmental conditions. The local random search mechanism and the environmental impacts are evaluated in simulations and in experimental case studies with software defined radios. This work is related to our current research described in section 3.3 since it analyses the underlying phase synchronisation method.

4.2 Receive collaboration in wireless sensor networks

In a collaboration with researchers from TecO at the Karlsruhe Institute of Technology (KIT), we have also studied a complementary beamforming method in which the receive nodes achieve the beamforming computation. In wireless sensor networks (WSN), the range of communication is always a limiting factor. Receive collaboration is a method for extending the reception range of a WSN by leveraging the multiple antennas present. This is done by recombining the noisy signals received by every node in the network and in the process filtering out the individual noise received at each node. One method carrying out this process is collaborative channel equalization (CCE) which allows nodes to collaboratively remove noise from the received signal. In [3] we analyse the feasibility of receive collaboration based on experimental examinations. Then the energy efficiency and the cost in terms of computational load and memory required are calculated. The results indicate that receive collaboration efficiently increases the reliability, energy efficiency and quality of service. Although the improvements are at the expense of increased computational load and memory demands, receive collaboration is quite useful, especially when inter-node distances are relatively small with respect to the incoming noisy signal or when the communication of rather long data streams is considered. Furthermore, its scalability and flexibility make it applicable for a wide range of WSN applications. Figure 10 illustrates the experimental setting utilised.

Publications by other authors

[1] Robert G. Brown. Dieharder: A random number test suite. http://www.phy.duke.edu/ rgb/General/dieharder.php, 2011.

[2] N.H. Kuiper. Tests concerning random points on a circle. In *Proceedings of the Koinklijke Nederlandse Akademie van Wetenschappen*, volume Series a 63, pages 38–47, 1962.

Own publications (Reviewed and accepted)

[3] Behnam Banitalebi, Stephan Sigg, Dawud Gordon, Takashi Miyaki, and Michael Beigl. Receive collaboration in wireless sensor networks; analyzing and performance evaluation. In *Proceedings of the 8th IEEE International Conference on Mobile Ad-hoc and Sensor Systems*, 2011.

[4] Dawud Gordon, Stephan Sigg, Yong Ding, and Michael Beigl. Using prediction to conserve energy in recognition on mobile devices. In *Proceedings of the 9th IEEE International Conference on Pervasive Computing and Communications (PerCom2011)*, 2011.

[5] Predrag Jakimovski, Florian Becker, Stephan Sigg, Hedda R. Schmidtke, and Michael Beigl. Collective communication for dense sensing environments. In *7th IEEE International Conference on Intelligent Environments (IE)*, 2011. (**Best paper**).

[6] Markus Reschke, Sebastian Schwarzl, Johannes Starosta, Stephan Sigg, and Michael Beigl. Context awareness through the rf-channel. In *Proceedings of the 2nd workshop on Context-Systems Design, Evaluation and Optimisation*, 2011.

[7] Markus Reschke, Johannes Starosta, Sebastian Schwarzl, and Stephan Sigg. Situation awareness based on channel measurements. In *Proceedings of the fourth Conference on Context Awareness for Proactive Systems (CAPS)*, 2011.

[8] Markus Scholz, Stephan Sigg, Dimana Shihskova, Georg von Zengen, Gerrit Bagshik, Toni Guenther, Michael Beigl, and Yusheng Ji. Sensewaves: Radiowaves for context recognition. In *Video Proceedings of the 9th International Conference on Pervasive Computing (Pervasive 2011)*, 2011.

[9] Stephan Sigg. Context-based security: State of the art, open research topics and a case study. In *Proceedings of the 5th ACM International Workshop on Context-Awareness for Self-Managing Systems (CASEMANS 2011)*, 2011.

[10] Stephan Sigg and Michael Beigl. Distributed adaptive expectation aware in-network context processing. In *Proceedings of the 4th ACM International workshop on Context-Awareness for Self-Managing Systems in conjunction with Ubicomp 2010*, September 2010.

[11] Stephan Sigg and Michael Beigl. An adaptive protocol for distributed beamforming. In *17. Fachtagung 'Kommunikation in Verteilten Systemen 2011' (KiVS11)*, 2011.

[12] Stephan Sigg, Michael Beigl, and Behnam Banitalebi. *Efficient adaptive communicatoin from multiple resource restricted transmitters*, chapter 5.4. Organic Computing - A Paradigm Shift for Complex Systems, Autonomic Systems Series. Springer, 2011.

[13] Stephan Sigg, Matthias Budde, Yusheng Ji, and Michael Beigl. Entropy of audio fingerprints for unobtrusive device authentication. In *Poster Proceedings of the 7th International and Interdisciplinary Conference on Modeling and Using Context (Context2011)*, 2011.

Own publications (Submitted documents)

[14] Dominik Schuermann and Stephan Sigg. Secure communication based on ambient audio. *Transactions on mobile computing*, Submitted in 2011.

[15] Stephan Sigg and Yusheng Ji. Pintext: A framework for secure communication based on context. In *Submitted to the Eighth Annual International Conference on Mobile and Ubiquitous Systems:Computing, Networking and Services (MobiQuitous 2011)*, 2011.

[16] Stephan Sigg and Yusheng Ji. Accelerating distributed adaptive transmit beamforming: Local random search, a sharp asymptotic bound, simulations and a case study. In *Submitted to the 31st Annual IEEE International Conference on Computer Communications (IEEE INFOCOM 2012)*, 2012.