

Lehrstuhl für Kommunikationsnetze
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Wireless Communication for Personal Safety Services

– Sensing, Localization and Alarming –

**Genehmigte Dissertation
zur Erlangung des akademischen Grades
Doktor der Ingenieurwissenschaften (Dr.-Ing.)
der Fakultät für Elektrotechnik und Informationstechnik
der Technischen Universität Dortmund**

von

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Dissertation eingereicht am:	26. August 2011
Tag der mündlichen Prüfung:	26. Januar 2012

Dortmunder Beiträge zu Kommunikationsnetzen und -systemen

Band 4

Andreas Lewandowski

Wireless Communication for Personal Safety Services

Sensing, Localization and Alarming

D 290 (Diss. Technische Universität Dortmund)

Shaker Verlag
Aachen 2012

Bibliographic information published by the Deutsche Nationalbibliothek

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at <http://dnb.d-nb.de>.

Zugl.: Dortmund, Technische Univ., Diss., 2012

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Printed in Germany.

ISBN 978-3-8440-0862-3

ISSN 1867-4879

Shaker Verlag GmbH • P.O. BOX 101818 • D-52018 Aachen

Phone: 0049/2407/9596-0 • Telefax: 0049/2407/9596-9

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Abstract

This thesis provides novel concepts and performance evaluations for enhancing the personal safety in industrial plants and during rescue operations of fire brigades and technical emergency services by deploying wireless sensor services. In order to detect sources of danger more precisely and to generate a holistic operational picture of the incident scene, not only infrastructure components will be equipped with sensors; the concept of this thesis foresees the application of wireless connected environmental and vital sensors among employees and emergency personnel. As the focus of this thesis is aligned on safety critical applications, the end users of the system require high precise position information of measured sensor values, high reliability, robustness and availability even under extreme operational conditions.

The goal of this thesis is the design and performance evaluation of selected components for a mobile communication system for sensor-based monitoring, localization and alarming. The special contribution of this thesis is the presentation and detailed validation of solution approaches that enable to address scenarios with exceedingly challenging requirements.

This objective is particularly addressed in the first reference scenario by avoiding explosions in an industrial underground plant, where -due to the hostile environment- new algorithms for RF-based indoor localization have been developed. The evaluation has been accomplished by detailed simulation models and extensive measurement campaigns in the application scenario. It has been demonstrated that the newly developed algorithms enhance the achievable positioning accuracy by almost 90% by reducing the self-interference effects of the system.

On the basis of a second reference scenario –a wide-area forest fire, which is not covered by public cellular networks– a new approach for transmitting text and sensor data over the GALILEO satellite system has been designed and specified. Based on an own developed stochastic simulation model of the satellite system and on analytical modeling for the expected latency, results of the optimization for a low-latency, worldwide available emergency service are provided.

A basic component of both solution approaches is local wireless communication technology operating in the 2.4GHz band, where coexistence interference within the system setup and also with neighboring networks occurs. Therefore, this thesis presents a comprehensive study on the interference behavior especially for the robust IEEE802.15.4a-CSS¹ standard, which is also used for indoor localization.

For rounding up the system design, a comprehensive routing concept has been developed by utilizing redundant connections for building up a new network topology in case of node failures. Furthermore, a novel concept for a Geo- and speech-based alarming service is presented, which can be used for controlling the rescue personal in both application scenarios.

The presented solutions of this thesis have been developed within and contributed to research projects, where industrial partners are involved. The developed system solutions have been validated by end users within the BMWi² project *Galileo4FireBrigades* by the fire brigades Dortmund and in the BMBF³ project *SAVE*⁴ by an operator of a huge industrial plant in practical operation. With more than 20 publications in international conferences and contributions to international journals, a broad resonance has been achieved. The results of the research will be included in various future projects, including the Collaborative Research Center SFB876 and a BMWi EXIST Research Transfer project.

¹CSS-Chirp Spread Spectrum

²BMW-Federal Ministry of Economics and Labor

³BMBF-Federal Ministry of Education and Research

⁴SAVE-Geographic Information System with Autonomous, Networked Gas Sensors

Kurzfassung

Die Personensicherheit in Industrieanlagen sowie bei Rettungseinsätzen von Feuerwehren und technischen Hilfsdiensten kann durch den Einsatz von Sensorsystemen stark gesteigert werden. Zur Detektion von Gefahren aller Art und Erlangung eines umfassenden Lagebilds sollen zunehmend nicht nur die Infrastruktur mit Sensoren ausgestattet werden, sondern auch Personen wie Mitarbeiter und Rettungskräfte mit drahtlos vernetzter Umgebungs- und Vitalsensorik. Für die Anwender ist dabei die hochgenaue Ortsreferenzierung der gewonnenen Informationen sowie die hohe Zuverlässigkeit, Robustheit und Verfügbarkeit des Gesamtsystems auch unter extremen Einsatzbedingungen essentiell.

Das Ziel dieser Arbeit ist der Entwurf und die Leistungsbewertung ausgewählter Komponenten eines mobilen Kommunikationssystems zur Sensor-basierten Messung, Lokalisierung und Alarmierung.

Der besondere Beitrag liegt dabei in der Vorstellung und umfassenden Validierung von Lösungsansätzen, die es ermöglichen, Szenarien mit besonders herausfordernden Anforderungen zu adressieren. Dies ist zum einen die Explosionsvermeidung in einer unterirdischen Industrieanlage, in der durch die funkfeindliche Umgebung neuartige Verfahren für eine Lokalisierung der Mitarbeiter in einem Störfall entwickelt werden mussten. Die Evaluierung der neu entwickelten Verfahren konnte durch detaillierte Simulationsmodelle und umfangreiche Messungen in dem realen Szenario durchgeführt werden. Es konnte hier gezeigt werden, dass durch die neu entwickelten Algorithmen (z.B. zur Reduktion der Eigeninterferenzen) die Genauigkeit der Lokalisierung bei gleichbleibenden Systemkosten um bis zu 90% erhöht werden konnte. Auf der Basis eines weiteren Referenzszenarios, einem großflächigem Waldbrand in einem nicht durch terrestrische Funkssysteme erschlossenen Gebiet, wurde in der Arbeit ein neuartiges Verfahren zur Übertragung von Notfallnachrichten mit dem Satellitennavigationssystem GALILEO entwickelt und spezifiziert. Auf der Basis eines eigens entwickelten, stochastischen Satellitenkommunikationsmodells, wie auch durch analytische Modellierung der Latenz, werden Ergebnisse einer Validierung sowie der optimierten Dimensionierung eines weltweit, mit sehr kurzen Verzögerungszeiten einsetzbaren, Notrufdienstes vorgestellt.

Eine wesentliche Basiskomponente beider Lösungsansätze sind lokale Funknetztechniken, die im 2,4 GHz-Band betrieben werden und sich gegenseitig stören sowie durch benachbarte Netze gestört werden. In dieser Arbeit wird daher eine Analyse der Interferenzeinflüsse auch unter Berücksichtigung des als besonders robust ausgewiesenen IEEE802.15.4a-CSS¹ Standards vorgestellt. Zur Abrundung des Systemdesigns wurden Routing Aspekte untersucht, um redundante Verbindungen bei Komponentenausfällen zum Aufbau einer neuen Netztopologie zu nutzen. Weiterhin wurde ein neuartiges Konzept für einen geo- und sprach-basierten Alarmierungsdienst erarbeitet, der in beiden Anwendungsszenarien für die zentrale Steuerung der Einsatzkräfte eingesetzt werden kann. Die in der Arbeit vorgestellten Forschungsergebnisse haben Eingang gefunden in Verbundprojekte, in denen neben Industriepartnern auch Anwender aktiv beteiligt waren. So konnten die entwickelten Systemkonzepte im BMWi² Projekt Galileo4Firebrigades durch eine Feuerwehr und im BMBF³ Projekt SAVE⁴ durch einen Betreiber einer sehr großen Industrieanlage auch im praktischen Betrieb validiert werden.

Durch über 20 Veröffentlichungen auf internationalen Konferenzen bzw. Beiträgen zu internationalen Journals konnte eine breite Resonanz erzielt werden. Die Ergebnisse der Forschung werden in Zukunft in verschiedene Folgeprojekte einfließen, unter anderem im Sonderforschungsbereich 876 und einem BMWI-EXIST-Forschungstransferprojekt.

¹CSS-Chirp Spread Spectrum

²BMWi-Bundesministerium für Wirtschaft und Technologie

³BMBF-Bundesministerium für Bildung und Forschung

⁴SAVE-Geographisches Informationssystem mit autonom vernetzten Einzel-Gassensoren

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List of Acronyms

ACK	Acknowledgement
ACM	Association for Computing Machinery
A-GPS	Assisted GPS
AN	Anchor Node
AoA	Angle of Arrival
AODV	Ad-Hoc On Demand Distance Vector
AP	Access Point
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
CAD	Computer-Aided Design
CCA	Clear Channel Assessment
CCK	Complementary Code Keying
CDF	Cumulated Density Function
CEB	Central Event Broker
CO	Carbon Monoxide
CO₂	Carbon Dioxide
CO₂	Component Object Model
CRLB	Cramer Rao Lower Bound
CS	Cospas Sarsat
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
CSS	Chirp Spread Spectrum
DBPSK	Differential Binary Phase Shift Keying
DECT	Digital Enhanced Cordless Telecommunications
D-GPS	Differential GPS
DKF	Discrete Kalman Filter
DQPSK	Differential Quadrature Phase Shift Keying
DSSS	Direct Sequence Spread Spectrum
EKF	Extended Kalman Filter
E-OTD	Enhanced Observed Time Difference
FFD	Full Functional Device
G4FB	Galileo for Fire Brigades (BMW _i Project)
GEO	Geostationary Earth Orbit
GeoGrid	Geocasting Protocol for MANET's based on Grid
GEOSAR	Geostationary Earth Orbit Search and Rescue
GeoTora	Geographic Extension of Temporally Ordered Routing Algorithm
GIS	Geographic Information System
Glonass	Gobalnaja Nawigazionnaly Sputnikowaja Sistema – Russian GNSS

Contents

GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSM	Global System for Mobile Telecommunications
H	Hydrogen
HF	High Frequency
ICMC	Incident Commander Mobile Client
IETF	Internet Engineering Task Force
IN	Infrastructure Node
INET	Internet Framework for OMNeT++
IP	Internet Protocol
IR	Infrared
ITPLA	Individual Transmission Power Level Adaptation
ITU-T	International Telecommunications Union - Telecommunication Standardization Sector
k-NN	k-Nearest Neighbor
LAN	Local Area Network
LBM	Location based Multicast
LEO	Low Earth Orbit
LEOSAR	Low Earth Orbit Search and Rescue
LOS	Line of Sight
LTE	Long Term Evolution
M2M	Machine2Machine
MAC	Medium Access Control
MAN	Metropolitan Area Network
MANET	Mobile Ad-Hoc Networks
MAX	MAXIM
MC	Mobile Client
MDS	Multi-Dimensional Scaling
MEO	Medium Earth Orbit
MEOSAR	Medium Earth Orbit Search and Rescue
MNME	Multiscale Network Modeling Environment
MOOSE	Mobile Object Simulation Environment
MPE	Mean Position Error
MT	Mobile Tag
NLOS	Non Line of Sight
OLSR	Optimized Link State Routing
OMNeT++	Network Simulator
OGC	Open Geospatial Consortium
OS	Open Service
PAN	Personal Area Network
PDA	Personal Digital Assistant
PDF	Probability Density Function
PER	Packet Error Rate

PESQ	Perceptual Evaluation of Speech Quality
PHY	Physical Layer
PLB	Personal Locator Beacon
PLC	Powerline Communications
PRS	Public Regulated Service
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RERR	Route Error
RERR-ACK	Route Error Acknowledgement
RF	Radio Frequency
RFD	Reduced Functional Device
RPS	Radiowave Propagation Simulator
RREP	Route Reply
RREQ	Route Request
RSSI	Received Signal Strength
RTLS	Real Time Localization System
RTof	Round Trip Time-of-Flight
SAR	Search-and-Rescue
SAVE	Geographic Information System with Autonomous Networked Gas Sensors (BMBF Project)
SCRP	Simulation Control and Result Processing
SDS-TWR	Symmetrical Double Sided-Two Way Ranging
SGW	Service Gateway
SMS	Short Message Service
SNIR	Signal-to-Noise and Interference Ratio
SNR	Signal-to-Noise Ratio
SoL	Safety of Life
SOS	Sensor Observation Service
SWE	Sensor Web Enablement
TC	Topology Control
TCM	Topology Control Message
TCP	Transfer Control Protocol
TDofA	Time-Difference-of-Arrival
TI	Texas Instruments
TKSE	ThyssenKrupp Steel Europe AG
ToA	Time-of-Arrival
TPLA	Transmission Power Level Adaptation
UDP	User Datagram Protocol
UMTS	Universal Mobile Telecommunication System
UWB	Ultra Wideband
VoIP	Voice over IP
WAN	Wide Area Network
Wi-Fi	Wireless Fidelity

Contents

WIN	Wireless Infrastructure Node
WLAN	Wireless Local Area Network
WMAN	Wireless Metropolitan Area Network
WPAN	Wireless Personal Area Network
WSN	Wireless Sensor Networks
WToA	Weighted-Time-of-Arrival
WWAN	Wireless Wide Area Network