Department of Communications and Networking

Media Access Control and Time Synchronization in Delay-Sensitive Multi-Channel Wireless Sensor Networks

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Jari Nieminen

Aalto University

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Media Access Control and Time Synchronization in Delay-Sensitive Multi-Channel Wireless Sensor Networks

Jari Nieminen

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Abstract

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Abstract

Wireless Sensor Networks (WSNs) consist of sensor nodes that measure the environment and one or more gateway nodes that collect the wirelessly sent information from sensor nodes. Wireless systems are free from the constraints of cables while they provide low installation costs, ease of maintenance, and flexibility. Hence, it is natural that WSNs offer an interesting solution for an innumerable number of applications although the exploitation of wireless networks brings new challenges as well because of shared and unreliable transmission media. Improving robustness and efficiency, together with the minimization of communication delays are the most important research challenges en route towards the large-scale implementation of WSNs.

Media Access Control (MAC) protocols are responsible for sharing the transmission media among sensor nodes and avoiding collisions of transmissions. Motivation for the research of multi-channel MAC protocols is due to the fact that the performance of a wireless network can be significantly enhanced using multiple frequency channels simultaneously. Multi-channel communications can be used for minimization of delay which is crucial in delay-sensitive applications, such as in wireless automation and target tracking. Time synchronization is essential for many WSN applications and the use of multi-channel communications enables faster execution of the synchronization process which improves network efficiency. Most current WSNs use unlicensed parts of the frequency spectrum which have become very crowded lately. Cognitive Radio (CR) technology can be used in WSNs to avoid problems related to coexistence with other systems and enable efficient spectrum use.

In this thesis a novel multi-channel MAC protocol is presented that has been designed especially to correspond to the requirements of WSN applications. By means of theoretical analysis it is shown that the proposed protocol outperforms other existing solutions with respect to delay, which is of significant importance for many WSN applications. Impacts of multi-channel communications on wireless automation and target tracking are investigated and the results show the interdependencies between communication and application parameters. In addition to these topics, a novel multi-channel time synchronization protocol is presented and practical issues related to time synchronization in CR networks are studied.

Keywords Media access control, multi-channel communications, time synchronization, wireless sensor networks, cognitive radio networks

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Tiivistelmä

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Tekijä
Jari Nieminen

Väitöskirjan nimi
Siirtomedian hallinta ja aikasynkronointi viiveherkissä monikanavaisissa langattomissa sensoriverkoissa

Julkaisija Sähkötekniikan korkeakoulu

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Tiivistelmä

Langattomat sensoriverkot koostuvat sensorisolmuista, jotka mittaavat ympäristöä, sekä yhdestä tai useammasta yhdyskäytäväsolmusta, jotka keräävät sensorien langattomasti lähettämän informaation. Langattomat järjestelmät ovat vapaita kaapelien rajoituksista samalla tarjoten matalia asennuskustannuksia, ylläpidon helppoutta sekä joustavuutta. Näin ollen on luonnollista, että langattomat sensoriverkot ovat kiinnostava ratkaisu lukemattomille sovelluksille, siitä huolimatta, että langattomien verkkojen hyötykäyttö tuo myös uusia haasteita jaetun, epäluotettavan siirtomedian vuoksi. Robustisuuden ja tehokkuuden parantaminen yhdessä tiedonsiirtoviiveiden minimoinnin kanssa ovatkin tärkeimpiä haasteita matkalla kohti laajamittaista langattomien sensoriverkkojen käyttöönottoa.

Media Access Control (MAC) -protokollat ovat vastuussa siirtomedian jakamisesta sensorisolmujen kesken ja lähetysten törmäysten välttämisestä. Monikavanaisten MAC-protokollien tutkimusta motivoi se, että langattoman verkon suorituskykyä voidaan merkittävästi parantaa käyttämällä useaa taajuuskaistaa samaan aikaan. Monikanavaista tietoliikennettä voidaan käyttää viiveen minimointiin, mikä on ratkaisevan tärkeää viiveherkissä sovelluksissa, kuten langattomassa automaatiossa ja kohteen seurannassa. Aikasynkronointi on välttämätöntä useille langattomien sensoriverkkojen sovelluksille ja monikanavaisen tietoliikenteen käyttö mahdollistaa synkronointiprosessin nopeamman suorittamisen, mikä parantaa verkon tehokkuutta. Useimmat langattomat sensoriverkot käyttävät lisensoimattomia spektrin osia, joista on tullut hyvin ruuhkaisia viimeaikoina. Kognitiiviradioiden teknologiaa voidaan käyttää langattomissa sensoriverkoissa eri järjestelmien rinnakkaiseloon liittyvien ongelmien välttämiseksi ja mahdollistamaan tehokas spektrin käyttö.

Tässä väitöskirjassa esitellään uusi, erityisesti langattomien sensoriverkkosovellusten vaatimuksia vastaamaan suunniteltu monikavanainen MAC-protokolla. Teoreettisen analyysin avulla osoitetaan, että ehdotettu protokolla suoriutuu paremmin kuin muut olemassaolevat ratkaisut viiveen suhteen, mikä on hyvin tärkeää monille langattomien sensoriverkkojen sovelluksille. Monikanavaisten tietoliikennejärjestelmien vaikutusta langattomaan automaation sekä kohteen seurantaan tutkitaan ja tulokset näyttävät tietoliikenne- ja sovellusparametrien välisiä riippuvaisuuksia. Näiden aiheiden lisäksi työssä esitellään uusi monikanavainen aikasynkronointiprotokolla sekä tutkitaan kognitiiviradioverkoissa aikasynkronointiin liittyviä käytännön ongelmia.

Avainsanat Siirtomedian hallinta, monikanavainen tietoliikenne, aikasynkronointi, langattomat sensoriverkot, kognitiiviradioverkot

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Preface

After dedicating over 4 years of my life to the dissertation process, I have finally completed my Ph.D. studies. This has been a long journey, comparable to a roller-coaster ride with many ups and downs. Many people have assisted and supported me in the course of this process which was extremely important, especially during the hard times. Next, I would like to express my gratitude to the people who have helped me in the accomplishment of this Ph.D. degree.

First, I would like to thank my supervisor, Prof. Jäntti, for everything he has done for me during these years. He has been a great mentor. Moreover, it has been a priviledge to work with Dr. Qian from Prairie View A&M University, Texas, USA. At our university, I thank Mr. Husso, Shekar, Jussi, Mikael, et al. for collaboration, fruitful discussions and pleasant work athmosphere. I would also like to thank the pre-examiners of this thesis, Prof. Koivisto and Prof. Elmusrati, for their insightful comments. In addition, I thank Dr. Altosaar for proof-reading of the thesis. The financial support from Nokia Foundation is gratefully acknowledged.

For me it was crucial to get my mind off the thesis once in a while and I would like to thank my friends for making that possible. Just to name a few, I thank Jukka, Vepä, Anssi, and Jussi for providing various extra-curricular activites during these years. Furthermore, I would like to thank my team-mates in Otaniemen Jyllääjät (OJy) and Köyhät Ritarit (KöyRi) as well.

Last but not least, I would like to express my greatest gratitude to my family. I thank my beloved girlfriend, Heidi, for being there when I needed you the most and inspiring me during the times of despair. I am also indebted to my parents and syster for their unwavering support and continuous encouragement. I think my family often had more faith in me than I did in myself during this process.

Thank you all, I would not have been able to pull this off without you.

Espoo, February 13, 2012,

Jari Nieminen

Contents

List of Publications

This thesis consists of an overview and of the following publications which are referred to in the text by their Roman numerals.

I S. Nethi, J. Nieminen, and R. Jäntti. Exploitation of Multi-Channel Communications in Industrial Wireless Sensor Applications: Avoiding Interference and Enabling Coexistence. In *Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC)*, Cancun, Mexico, pages 345–350, March 2011.

II J. Nieminen and R. Jäntti. Delay-Throughput Analysis of Multi-Channel MAC Protocols in Ad Hoc Networks. *EURASIP Journal on Wireless Communications and Networking, Special Issue on Quality of Service in Wireless Networks*, Volume 2011, Issue 108, pages 1–15, September 2011.

III J. Nieminen, M. Björkbom, R. Jäntti, and L. Eriksson. Multi-Channel Communications in Event-Based Automation: Interdependencies between Communication and Control Parameters. *International Journal of Distributed Sensor Networks*, Accepted for publication, In Press, December 2011.

IV J. Nieminen, J. Eriksson, and R. Jäntti. Performance of Target Tracking Applications in Multi-Channel Wireless Sensor Networks. *IEEE Wireless Communications and Networking Conference (WCNC)*, Accepted for publication, Paris, France, April 2012.

V J. Nieminen, L. Qian, and R. Jäntti. Time Synchronization of Cognitive Radio Networks. In *Proceedings of the IEEE Global Telecommunications Conference (GLOBECOM)*, Honolulu, HI, USA, pages 1–6, November 2009.

VI J. Nieminen, L. Qian, and R. Jäntti. Network-wide Time Synchronization in Multi-Channel Wireless Sensor Networks. *Wireless Sensor Network*, Volume 3, Issue 2, pages 39–53, February 2011.

VII J. Nieminen, R. Jäntti, and L. Qian. Primary User Detection in Distributed Cognitive Radio Networks under Timing Inaccuracy. In *Proceedings of the IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (DYSPAN)*, Singapore, Singapore, pages 1–8, April 2010.

VIII J. Nieminen, L. Qian, and R. Jäntti. Suppression of Intra-Network Interference in Decentralized Cognitive Radio Networks under Timing Errors. In *Proceedings of the 4th International Conference on Signal Processing and Communication Systems (ICSPCS)*, Gold Coast, Australia, pages 1–7, December 2010.

Author's Contribution

Publication I: "Exploitation of Multi-Channel Communications in Industrial Wireless Sensor Applications: Avoiding Interference and Enabling Coexistence"

The author designed the protocol together with S. Nethi. The theoretical analysis was carried out by the author. The author assisted S. Nethi in developing the simulation scenario while R. Jäntti supervised the work.

Publication II: "Delay-Throughput Analysis of Multi-Channel MAC Protocols in Ad Hoc Networks"

The author derived the theoretical results, carried out the simulations, and wrote the entire paper under the guidance of R. Jäntti.

Publication III: "Multi-Channel Communications in Event-Based Automation: Interdependencies between Communication and Control Parameters"

The author deduced the theoretical results for the communication system. Moreover, the author was responsible for and wrote most of the results presented in the paper by exploiting the theoretical results of control systems derived by M. Björkbom and L. Eriksson. The paper was written under the supervision of R. Jäntti.

Publication IV: “Performance of Target Tracking Applications in Multi-Channel Wireless Sensor Networks”

The author developed the used formulas and generated the simulation scenario as well as the simulation results. The author wrote the entire paper with the help of R. Jäntti and J. Eriksson.

Publication V: “Time Synchronization of Cognitive Radio Networks”

The author developed the proposed protocol together with L. Qian. The theoretical results were derived by the author. The paper was written under the supervision of R. Jäntti.

Publication VI: “Network-wide Time Synchronization in Multi-Channel Wireless Sensor Networks”

The author developed the proposed protocol together with L. Qian. The theoretical derivations and simulations were carried out by the author while L. Qian designed the root node selection algorithm. The paper was written under the supervision of R. Jäntti.

Publication VII: “Primary User Detection in Distributed Cognitive Radio Networks under Timing Inaccuracy”

The author derived the theoretical model with the help of R. Jäntti. The author was responsible for generating all the results and writing the entire paper. L .Qian contributed at the idea level and revised the paper.

Publication VIII: “Suppression of Intra-Network Interference in Decentralized Cognitive Radio Networks under Timing Errors”

The author wrote most of the paper and carried out all the simulated results. In addition, the author constructed and solved the optimization problem together with L. Qian. The paper was written under the supervision of R. Jäntti.

Nomenclature

List of Abbreviations

ACU	Air Conditioning Unit
ATIM	Ad Hoc Traffic Indication Message
B-MAC	Berkeley Media Access Control
BEB	Binary Exponential Backoff
BP	Beacon Period
CAM-MAC	Cooperative Asynchronous Multi-Channel MAC
CAP	Contention Access Period
CCC	Common Control Channel
CCS	Crane Control System
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CDP	Contention plus Data Period
CFP	Contention Free Period
CHMA	Channel-Hopping Multiple Access
CR	Cognitive Radio
CRSN	Cognitive Radio Sensor Network
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear to Send
ECC	European Communications Committee

EKF	Extended Kalman Filter
FDMA	Frequency Division Multiple Access
FOLIPD	First Order Lag plus Integrator plus Delay
FTSP	Flooding Time Synchronization Protocol
G-McMAC	Generic Multi-channel MAC
GPS	Global Positioning System
GSM	Global System for Mobile Communications, originally Groupe Spécial Mobile
GW	Gateway node
HB	Hierarchy Beacon
HD	Hierarchy Discovery
i.i.d.	independent, identically distributed
IEEE	Institute of Electrical and Electronics Engineers
IMC	Internal Model Control
IoT	Internet of Things
ISA	International Society of Automation
ISCR	Interference Suppression for Cognitive Radios
ISE	Integral Square Error
ISM	Industrial, Scientific and Medical
ITU-R	Radio Communication Sector of International Telecommunication Union
LQG	Linear Quadratic Gaussian
LTS	Lightweight Tree-based Synchronization
MAC	Media Access Control
MANET	Mobile Ad Hoc Network
MCTS	Multi-Channel Time Synchronization
MHMS	Machine Health Monitoring System

MMAC	Multi-channel MAC
NCS	Networked Control System
NI	Negotiation Interval
NTP	Network Time Protocol
OFDM	Orthogonal Frequency Division Multiplexing
PBS	Pairwise Broadcast Synchronization
PID	Proportional-Integral-Derivative
PTP	Precision Time Protocol
QoS	Quality of Service
RBS	Reference Broadcast Synchronization
RsACK	Resource ACKnowledgement
RsREQ	Resource REQuest
RTS	Request to Send
S-MAC	Sensor MAC
SE	Synchronization Execution
SENDORA	SEnsor Network for Dynamic cOgnitive Radio Access
SN	Synchronization Negotiation
SNR	Signal to Noise Ratio
Sreq	Synchronization request
Sres	Synchronization response
SYN-MAC	Synchronized MAC
TDMA	Time Division Multiple Access
TDOA	Time Delay of Arrival
TDP	Time Diffusion Protocol
TPSN	Timing-sync Protocol for Sensor Networks
TRAMA	Traffic-Adaptive Medium Access

TSMP	Time Synchronized Mesh Protocol
UB	Uniform Backoff
WiseMAC	Wireless Sensor MAC
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network
WRAN	Wireless Regional Area Network
WSN	Wireless Sensor Network
Z-MAC	Zebra MAC

List of Greek Symbols

$\Gamma(\alpha)$	Gamma function
$\Gamma(\alpha, \beta)$	Incomplete Gamma function
γ	Clock drift
δ_{max}	Jitter margin
Θ	Clock offset
θ	Clock skew
θ_A	Node A's clock skew
θ_B	Node B's clock skew
λ_L	Sensing threshold
ρ	Maximum number of retransmissions
σ_b	Standard deviation of received signal power in block b
σ_w^2	Variance of noise
τ	Length of a time slot
τ_s	Length of the sensing slot
ω	Size of the backoff window
ω_a	Angular frequency
ω_b	Weight of a signal block b

ω_b^*	Optimal weight of a signal block b

List of Latin Symbols

a	Tuning parameter
B	Number of blocks
b	Index of a block
C	Capacity of the secondary network
$C(s)$	Controller in Laplace domain
D	Media access delay
D_0	Initial media access delay
$\bar{D}$	Average access delay
$\bar{D}_0$	Initial access delay on average
$\bar{D}_{block}$	Additional delay of MMAC due to the contention process on average
d	Propagation delay
$F(D)$	CDF of delay
g	Arrival rate of the Poisson process
g_a	Arrival rate of MMAC
g_s	Arrival rate of SYN-MAC
$H(t)$	Clock model
H_0	Hypothesis: primary user not present
H_1	Hypothesis: primary user is present
$\bar{H}$	Expected number of hierarchy levels
J_{ISE}	Performance criterion
k_d	Derivative gain of the PID controller
k_i	Integral gain of the PID controller
k_p	Proportional gain of the PID controller
L	Decision metric

L_d	Delay constant of the controller
$\tilde{L}_w$	Weighted decision metric
M	Number of nodes (network size)
M_{slaves}	Maximum number of slave nodes
N	Number of channels
N_b	Number of samples in each block
$\tilde{N}$	Number of samples
O_{MCTS}	Approximation of the convergence time of MCTS
p	Transmission probability of p-persistent CSMA
$P(D)$	Probability that the delay of a packet is D
$P(s)$	Process function in Laplace domain
P_b	Probability that the channel is busy
P_c	Probability of collision
P_f	Probability of false alarm
P_s	Probability of successful transmission
P^c_{block}	Probability that a node cannot reserve resources during an ATIM window due to a shortage of data channels
P^d_{block}	Probability that a node cannot reserve resources during an ATIM window due to the end of a contention window
P_{occ}	Probability that all data channels are occupied
R	Number of retransmissions
$r(i,j)$	j^{th} sample in a signal block i
$r(n)$	Received signal
S	Throughput
s	Laplace variable
$s(n)$	Received signal from the primary user
T	Packet size in time slots τ

T_1	Send time stamp of the slave
T_2	Receive time stamp of the master
T_3	Send time stamp of the master
T_4	Receive time stamp of the slave
T_c	Length of a cycle
T_s	Length of the contention window in SYN-MAC
T_{atim}	Length of the ATIM window in MMAC
$w(n)$	Received noise
X	Number of transceivers
y_m	Process output
y_r	Reference output
$z(n)$	Received interference from other secondary users

List of Figures

1. Introduction

1.1 Introduction to Wireless Sensor Networks and Applications

State-of-the-art Wireless Sensor Network (WSN) technology enables design and implementation of novel and intriguing applications that can be used to address numerous industrial, environmental, societal, and economical challenges. A WSN generally consists of one or more gateways which collect and possibly process the measured information from a number of sensors via a radio link. Furthermore, wireless sensor nodes that constitute a WSN include a sensor interface, microcontroller, memory, and battery units, together with a radio module. Hence, wireless sensor nodes are able to carry out distributed sensing and data processing, and share the collected data using wireless communications.

WSNs differ from traditional wireless communications systems, such as cellular mobile phone networks, in many ways. Typical WSN implementations are distributed and have little predetermined infrastructure. The number of deployed sensor nodes may vary significantly depending on the application in question, from less than ten nodes to thousands. While designing communication protocols for WSNs it should be taken into account that nodes may be deployed in an ad hoc manner, due to the environment or large number of deployed nodes and consequently, important networking aspects of WSNs include flexibility and scalability.

Feasibility of WSNs from the economic perspective requires cost efficiency and due to the possibly large number of nodes, the manufacturing expenses of sensors should be as low as possible. This requirement, together with the small physical size of sensors introduce several design and resource constraints. Since sensor nodes are battery powered and have limited energy available, energy conservation is essential to maximize network lifetime. Short communication ranges and limited bandwidths of sensor nodes lead to multi-hop communications and low data rates, respectively. Moreover, the limited processing power and memory capacity of tiny, low-cost sensor nodes means that light-weight networking solutions are required to minimize complexity. Design constraints of networking solutions for WSNs are application dependent since different applications have specific critical requirements for network protocols such as simplicity, delay-sensitivity, and reliable data delivery.

A large number of various sensors have been developed for different purposes of use. For example, it is possible to exploit seismic, acoustic, magnetic, visual, or thermal sensors [46] depending on the application in question. To name just a few typical use scenarios, sensors can be used to measure movement, humidity, pressure, and temperature [45]. The application domain of WSNs is broad ranging from military scenarios to health care solutions and from habitat monitoring to industrial applications [182].

Wireless communications are free from the physical constraints of communication cables which makes them a very alluring communication solution for many applications. Furthermore, wireless systems are preferred over wired because of low installation costs, ease of maintenance and flexibility. However, the design challenges of WSNs include reliability, robustness, interference and scalability issues [128]. Multi-channel communications can be used to address these challenges and provide high performance along with trustworthy delivery of packets [187]. Naturally, exploitation of multiple frequency channels simultaneously requires more intelligence from sensor nodes and novel WSN protocols.

In the past, development of WSNs has been driven by military applications where possible usage scenarios include battlefield surveillance, monitoring the status of troops, chemical attack detection, among others [8], [28], [174]. On the contrary, sensor networks can be exploited in medical applications such as monitoring patients in real-time in hospitals or in home health care [18], [77], [166]. WSNs can be used for monitoring animals and nature as well; in fact environmental WSNs have many potential uses like cattle or rainforest monitoring, studying the recovery of endangered species, and even for observing vineyards [19], [22], [30].

Even though most of the current WSN implementations distribute only simple measurement data in a network, wireless multimedia sensor networks have gained more and more attention lately due to the availability of low-cost cameras and microphones [7]. Visual sensors could be used in many applications, such as surveillance, monitoring, and virtual reality [147]. However, data rate requirements of such systems are significantly higher than required for transmitting simple sample information. In addition, it has been foreseen that WSNs will become a notable part of the Internet of Things (IoT) [14], i.e., enabling the monitoring of the state of real-world objects by sensors and then searching for this information using an Internet browser in real-time. This would increase the importance of WSNs and they may indeed significantly affect the daily lives of many people already in the near future.

Many current industrial sensor applications employ wired systems but the indisputable benefits of wireless communications have lead to an increasing interest on the utilization of wireless technology in industrial networks [173]. Although development is still ongoing and open research issues still exist in this field, the urgent demand for low-cost wireless automation systems drives the research [51]. As an example, industrial WSN applications include mobile robots [131], tracking of components [79], chemical plants [25], and paper mills [135].

From the communication engineering point of view, the large number of possible applications introduces unforeseen challenges for which classical communication solutions are not suitable. However, smart sensors give us tools for finding answers to these new problems. Although a large number of communication protocols have been designed for specific applications, the lack of a generic solution leads to problems with respect to large scale economic success. Since the versatility of WSN applications is unimaginable and the amount of possible operation scenarios is unlimited, designed protocols should be suitable for various purposes of use. Consequently, scalability and flexibility of technical solutions are extremely important to enable the economic feasibility of WSNs.

The main characteristics of industrial WSNs are [51]:

1. Limited resources such as energy, memory, and processing power.

2. Harsh operation environments and dynamic network topologies.

3. Stringent Quality of Service (QoS) requirements, e.g., respecting the effect of delay in many applications.

4. Data redundancy due to high network density and correlation between

successive measurements.

5. Packet errors and variability of link capacities due to the wireless transmission media.

6. Security against attacks and intrusion.

7. The ad hoc nature of communications and possibly large networks.

8. Integration with other networks to enable coexistence of multiple networks and the Internet to enable remote usage.

This thesis considers especially items 2, 3, 5, 7 and 8, and strives to solve these challenges by exploiting multi-channel communications. In addition, some practical aspects are considered related to coexistence of multiple networks together with time synchronization issues. The focus of this thesis is especially on delay-sensitive WSN applications. Power conservation related issues are not included since energy-efficiency issues in WSNs have been already widely studied, see, e.g., [11].

1.2 Motivation and Objectives of the Thesis

The performance of a wireless network can be improved by using multiple frequency channels simultaneously to ensure robustness, minimize delay, and/or enhance throughput. Therefore, it is natural to assume that multi-channel communications will form the basis of various future wireless systems. Furthermore, most of the current WSNs operate on crowded and unlicensed frequency bands which causes coexistence problems with other wireless systems especially in industrial WSN applications. Multi-channel communications can be utilized to improve the performance under interference conditions and enable the coexistence of different applications. Since contention-based Media Access Control (MAC) protocols are simple to implement, flexible, and well suited for event-based sensor applications, it is desirable to design an efficient contention-based multi-channel MAC protocol for WSNs.

The main objective of this thesis is to study the utilization of multi-channel communications in wireless sensor networks. In this thesis a novel multi-channel MAC protocol designed especially for industrial WSNs is presented. The foundation and motivation behind the design of a new MAC protocol is to develop a simple, flexible, and delay efficient MAC protocol that improves the performance of industrial WSNs. Furthermore, when designing MAC protocols it is important to understand the trade-off between delay and throughput. The performance of different multi-channel MAC approaches is investigated to gain knowledge about the pros and cons of different MAC designs. The exploitation of multiple channels simultaneously has an impact on the used application as well, and thus the impact of the proposed MAC protocol on different applications is studied by considering wireless automation and target tracking scenarios.

Time synchronization is of significant importance for many applications and multiple frequency channels can be used simultaneously to minimize the convergence time of the synchronization process. Hence, a novel time synchronization protocol, which utilizes multi-channel communications, is proposed. Additionally, industrial WSNs are often located in such locations that multiple networks occupy the same spatial domain. It has been suggested that Cognitive Radio (CR) technology could be exploited in WSNs to avoid coexistence problems and increase the available spectrum [53]. This has provided motivation to investigate practical problems related to time synchronization in CR networks.

1.3 Contributions of the Publications

In Publication I a novel multi-channel MAC approach designed especially for industrial WSNs is proposed, entitled Generic Multi-channel MAC protocol (G-McMAC). The presented theoretical results imply that G-McMAC outperforms other existing solutions. However, the main contributions of Publication I are the design of the protocol together with simulation results from an industrial scenario which demonstrate the applicability of G-McMAC for industrial WSNs.

In Publication II the perfomance of multi-channel MAC protocols in ad hoc networks is analyzed. Average access delays and throughputs are deduced for different multi-channel MAC approaches in case of Poisson arrivals. The correctness of theoretical results is verified by simulations while the performance of the protocols is evaluated with respect to various critical operation parameters like the number of available channels, packet size, and arrival rate. It is shown that G-McMAC outperforms other existing solutions such as split phase [145] and periodic hopping [78] approaches with respect to the expected access delay while stable. In addition, G-McMAC also achieves the highest throughput in many cases.

In Publication III the impact of multi-channel communication on wireless automation is studied by considering how the critical communication parameters affect the performance of control systems. Furthermore, the constraints imposed by the control system on the used wireless network are demonstrated. The results of the paper indicate the trade-off between the performance of the wireless multi-channel communication system and the automation system.

In Publication IV the performance of networked estimation in contention-based multi-channel wireless networks is analyzed by focusing especially on the delay introduced by the MAC layer. An extended Kalman filter [124] is used for target tracking and since some packets may be lost due to the random contention process, the Kalman filter has to operate under observation losses which degrades estimation performance. The probability of packet loss is derived by using a Markov chain which is then used to investigate the relationship between communication and estimation parameters.

In Publication V a time synhcronization protocol which exploits multiple frequency bands simultaneously in order to minimize the convergence time of the synchronization process is proposed. Simple theoretical results are presented to demonstrate the gain compared with a single-channel time synchronization scheme.

In Publication VI the work originally presented in Publication V is extended significantly by investigating important theoretical issues, such as the convergence time bounds for an individual node as well as for entire networks. Furthermore, the performance of the proposed protocol with respect to different operation parameters like the number of available channels, network density, and transmission range of nodes, is simulated and analyzed. A suitable solution for the root node selection problem is presented as well.

In Publication VII energy detection in CR networks under timing inaccuracy is studied and the effects of interference caused by other secondary users due to timing misalignments are discussed. A novel mathematical model for calculating the impact of interfering nodes on energy detection is presented together with closed-form solutions for the probabilities of detection and false alarm. The proposed model is verified by simulations.

In Publication VIII the work initiated in Publication VII is continued and a novel interference suppression algorithm to mitigate the impact of other CR users' transmissions on sensing is proposed. An optimization problem is derived and solved to determine the optimal weights of samples under intra-network interference. The presented simulation results show that by using the proposed algorithm the throughput of distributed secondary networks, in case of timing inaccuracy, can be improved while preserving sufficient protection for primary users.

1.4 Outline of the Thesis

The rest of this thesis is organized as follows. In Chapter 2 a literature review is presented which covers the work conducted by the scientific community in the field of multi-channel communications, networked control systems, time synchronization, and sensing in cognitive radio networks. Results of the publications are then summarized in Chapter 3. Finally, conclusions are given in Chapter 4.

2. Related Work

2.1 State of the Art in WSN MAC Protocols

In general, the performance of wireless networks is heavily dependent upon used Media Access Control (MAC) protocols. Efficient media access schemes are in fact considered as an essential part of any power-limited self-configurable wireless ad hoc network [50]. The main objective of the MAC layer is to enable collision-free transmissions in an effective manner, or at the very least, control interference caused by overlapping transmissions. In other words, the utilized MAC protocol defines the rules for accessing the physical layer and when nodes are allowed to transmit packets. Since omnidirectional antennas are widely used in current Wireless Sensor Network (WSN) implementations, directional antennas are excluded from this thesis and their impact on MAC design is omitted.

Wireless communication networks can be divided into two classes based on operation principles. In infrastructure networks, the functioning of a network relies on predetermined network infrastructure such as base stations and access points in different types of wireless systems. However, ad hoc networks are self-configurable and the operations of the network are distributed. Also, in ad hoc networks nodes function independently without obeying a predefined network controller. WSNs can be seen as a mixture of both approaches due to the existence of gateways which collect information from the network. Even though gateways can control operations, as in infrastructure networks, the dynamic nature of WSNs is similar to ad hoc networks and therefore decentralized solutions like those found in ad hoc networks are often preferred.

In principle, orthogonal data transmissions can be achieved using various traditional methods. First of all, the Frequency Division Multiple Access (FDMA) technique distributes data transmissions on different fre-

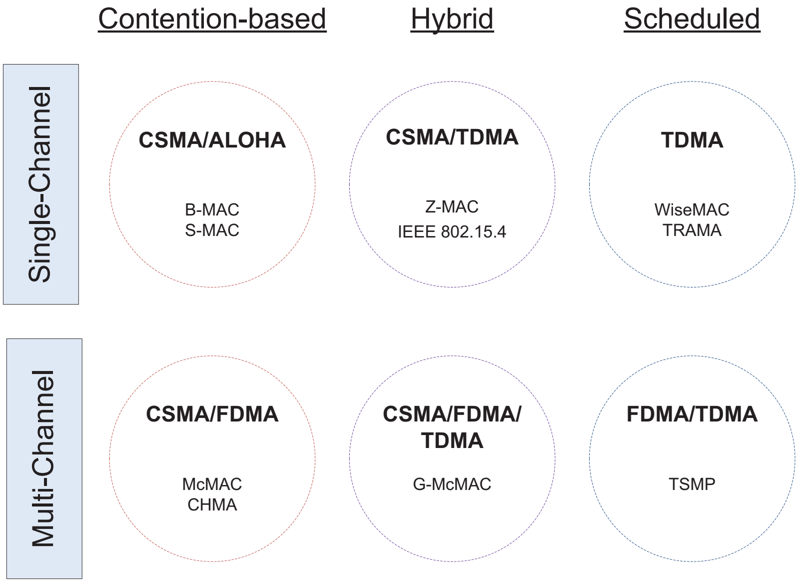


Figure 2.1. Classification of WSN MAC Protocols.

quency bands which are orthogonally spaced, i.e., the bands do not overlap. Moreover, the main purpose of Time Division Multiple Access (TDMA) schemes is to avoid collisions by ensuring that each user has its own time slot that determines when to transmit data. For example, a combination of FDMA and TDMA is used in the Global System for Mobile Communications (GSM) [12] to provide orthogonal multi-user access. For the case of spread spectrum systems Code Division Multiple Access (CDMA) can be exploited. In CDMA each user has its own orthogonal spreading code to provide efficient packet reception at the receiver. Even though several studies have been carried out related to the exploitation of CDMA in WSNs, see ,e.g., [33] and [169], in practice CDMA technology has not been used in WSNs yet, at least to the best of the author's knowledge.

A general classification of WSN MAC protocols is illustrated in Figure 2.1. Multi- and single-channel MAC protocols are divided into different categories according to their channel access method. One or two examples are given from each category as well. This is not an exhaustive list of protocols but rather a presentation of seminal protocols from different categories. Single-channel MAC protocols were discussed comprehensively in [52] and the protocols considered in this thesis were selected based from there. Scheduled MAC protocols allocate resources to avoid collisions whereas contention-based MAC algorithms do not reserve resources in advance. Hybrid MAC schemes aim to exploit the strengths of both approaches.

Traditional contention-based MAC schemes used in single-channel wireless systems are ALOHA [3] and Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) [76]. WSN MAC protocols in this class include Sensor MAC (S-MAC) [181] and Berkeley Media Access Control (B-MAC) [116]. Moreover, hybrid single-channel schemes use both CSMA and TDMA. Popular examples from this class are Zebra MAC (Z-MAC) [122] and the IEEE 802.15.4 standard [62]. In contrast to contention-based MAC protocols, scheduled single-channel MAC designs, such as Traffic-Adaptive Medium Access (TRAMA) [120] and Wireless Sensor MAC (WiseMAC) [38], use solely TDMA.

In case of multi-channel networks, typical contention-based protocols utilize CSMA and FDMA. Examples of such protocols are Channel-Hopping Multiple Access (CHMA) [161] and McMAC [144]. Furthermore, hybrid multi-channel MAC protocols use TDMA in addition to CSMA and FDMA. The only protocol in this category is Generic Multi-Channel MAC (G-McMAC) which is presented in Publication I. Finally, scheduled multi-channel MAC designs combine FDMA and TDMA and an example protocol in this category is Time Synchronized Mesh Protocol (TSMP) [115].

2.1.1 Single-Channel MAC Protocols

Even though we have lately witnessed the introduction of multi-channel WSNs [146], most of the present WSN implementations utilize only one carrier frequency at a time. As a consequence, research efforts in the field of MAC design for WSNs have concentrated on single-channel systems. For this reason, an innumerable number of single-channel MAC protocols have been proposed for WSNs [15]. In this section only the basic single-channel MAC approaches are presented together with a few major WSN MAC protocols [52]. Single-channel MAC protocols can be divided into the following classes based on operation characteristics. Scheduled MAC protocols utilize TDMA on a single frequency channel unlike contention-based MAC algorithms which allocate resources on the fly depending on the traffic. Additionally, hybrid MAC schemes try to exploit the pros and avoid the cons of both approaches to optimize the performance.

Contention-based MAC protocols are usually built on top of ALOHA or CSMA/CA. The basic operation of ALOHA is simple: if a node generates a packet it tries to transmit it immediately. In case of a collision the packet is delayed and retransmitted later on. This approach is often referred to as Pure ALOHA. To improve throughput, Slotted ALOHA was developed where time is divided into multiple time slots so that packets can be sent only at the beginning of a time slot [125]. On the other hand, in CSMA/CA the channel is first sensed to determine whether it is idle or not and then the resource request and the response messages are exchanged before the actual data transmission. This kind of message exchange mainly eliminates the *hidden node problem*, which occurs when several nodes that cannot hear each other transmit simultaneously causing packet collisions at the receiver, as experienced by ALOHA. Although CSMA/CA is widely used in different wireless systems, such as in IEEE 802.11 networks [61], its performance degrades under high traffic loads [20], [76].

Several variations of CSMA have been developed [155] since there needs to be a way to avoid the possibility of continuous collisions. In the *1-persistent* CSMA scheme, a packet is transmitted immediately if the channel is sensed idle. However, if the media is sensed busy, a node continues to listen to the channel until it becomes idle and then transmits immediately. This is a greedy approach which achieves the lowest delay as well as the lowest efficiency. Another option is to use the *p-persistent* CSMA protocol where new and retransmitted packets are transmitted with the same probability p. Delay and efficiency can be balanced by choosing p properly but the selection of p may become problematic in practice. The most common variation of CSMA, used in IEEE 802.11 networks for example [61], is *non-persistent* CSMA where a packet is transmitted immediately if the media is sensed idle on the first attempt. However, if a packet transmission is rescheduled due to the busy channel, the node waits for a random time before trying to access the channel again. While non-persistent CSMA achieves the highest efficiency it also induces the highest delays.

In case of collisions, 1- and non-persistent CSMA schemes schedule retransmissions randomly using a backoff counter. These random waiting times can be derived using, e.g., Uniform Backoff (UB) counters together with Binary Exponential Backoff (BEB). This means that the waiting time is chosen from a certain window by using a uniform distribution while the size of the backoff window is increased base 2 exponentially as a function of the number of retransmissions.

As an example of contention-based single-channel WSN MAC protocols, S-MAC [181] and B-MAC [116] are presented. The main goal of S-MAC is to reduce the energy consumption. The measurement results show that it achieves a 2-6 times lower energy consumption than an 802.11-like MAC. This is achieved by using periodic sleeping and setting radios off while other nodes are transmitting. Nevertheless, according to [116], B-MAC seems to outperform S-MAC in terms of packet delivery rate, throughput, and delay while also consuming less energy. B-MAC exploits an adaptive preamble sampling scheme to minimize energy consumption while it supports reconfiguration during operation.

Many hybrid single-channel MAC protocols have been proposed for WSNs. For example, in the IEEE 802.15.4 standard [62] the hybrid approach is exploited by using Contention Free Periods (CFPs) and Contention Access Periods (CAPs). The IEEE 802.15.4 standard is designed for Wireless Personal Area Networks (WPANs) and is widely used in WSNs. Nevertheless, the MAC solution used in this standard does not permit utilization of multiple frequency channels simultaneously. Another popular protocol in this class is Z-MAC [122]. In case of low traffic, Z-MAC utilizes CSMA to provide high channel utilization and low delays. However, in case of high traffic, Z-MAC achieves good performance by using TDMA. Z-MAC seamlessly switches between CSMA and TDMA during the operation depending on traffic conditions.

Scheduled algorithms divide time into multiple time slots such that only a single transmission can take place in a collision domain at a time. The strength of this kind of an approach is that in case of stable channel conditions, fixed network topology, and periodic packet arrivals, transmissions can be scheduled in an optimized manner and no overhead is induced due to resource negotiations. Ideally, scheduled systems do not suffer from collisions and can guarantee fixed delays. In general, scheduled MAC protocols perform well under high traffic loads while suffering from network topology changes, irregular generation of packets, and inaccurate timing. Even though the calculation of an efficient schedule may be a challenging task it is possible to calculate optimal schedules in polynomial time, for example, for linear convergecast networks [185].

One of the first and most significant scheduled WSN MAC protocols is TRAMA [120]. It carries out a distributed election, based on the schedules announced by the transmitters. A random access procedure is utilized for signaling purposes while data transmissions take place during contention-free periods. The protocol strives for energy-efficiency by offering collision-free data transmissions and low-power modes for sensor nodes. However, some energy is wasted since all the nodes are awake for the entire contention period and scalability may be a problem as well. Moreover, WiseMAC [38] is a scheduled single-channel MAC protocol designed for minimizing energy consumption in infrastructure WSNs. The focus of WiseMAC is on the scheduling of downlink traffic from the gateway to sensor nodes. In WiseMAC, sensor nodes sleep most of the time and wake up every now and then for incoming data transmissions. The main disadvantage of the protocol is that it is not suitable for multi-hop networks.

2.1.2 Multi-Channel MAC Protocols

Instead of using only one channel for data transmission, it is possible to exploit multiple channels to improve the performance of a network [9]. Since only a few multi-channel MAC protocols have been designed especially for WSNs, the protocols proposed for ad hoc networks are considered in this subsection as well. MAC protocols in Cognitive Radio (CR) networks function often in a similar way as well and a comprehensive review of the protocols, designed especially for such systems, can be found from [31]. Nevertheless, CR MAC designs differ from ad hoc and WSN MAC protocols since in CR networks nodes need to be aware of their environment and avoid interfering with the primary system. Therefore, CR MACs generally include a sensing interval during which the presence of the primary system is determined.

In case of multi-channel MAC approaches the proposed protocols can be divided into three classes based on operation principles: scheduled, hybrid, and contention-based. Another distinction which categorizes the proposed algorithms is the amount of transceivers required for proper functioning. Furthermore, the division can be made based on the amount of rendezvous, use of a dedicated control channel, time synchronization requirements, or channel selection [167].

Scheduled multi-channel MAC algorithms divide resources into time-frequency blocks and then assign these blocks to different users for data transmissions. After the initialization phase, such protocols can operate energy efficiently since nodes can turn their radios off and "sleep" when they do not have to transmit or receive. In the context of WSNs, the most popular scheduled MAC protocol is TSMP [115] which is considered as the foundation of the WirelessHart protocol [146] and the ISA-SP100 standard by the International Society of Automation (ISA) [65]. Since TSMP is already used in many WSN applications, there are no major challenges related to the exploitation of multi-channel communications in WSNs in general. However, TSMP is a scheduled MAC protocol and hence, a novel contention-based protocol is required for event-based, delay-sensitive WSN applications.

Another scheduled multi-channel MAC designed for WSNs was proposed by Incel in her Ph.D. thesis [64]. In the thesis the performance of the proposed protocol was not compared with TSMP. This was most likely due to the fact that this work was published roughly at the same time as TSMP. The problems related to utilization of scheduled approaches include additional complexity and messaging. Scheduled MAC protocols do not perform well in case of mobility, network topology changes, large networks, or intermittent packet generation. Hence, this thesis concentrates on contention-based solutions.

The natural but very expensive way to design a multi-channel MAC protocol is to assume that we have enough receivers so that it is possible to listen to all channel simultaneously [105], [106]. On the other hand, busy tone schemes use an additional channel for signaling an occupied data channel and this approach solves the hidden node problem [2], [34], [157], [168], [175]. Nevertheless, these schemes actually use only one channel for data transmissions instead of multiple ones.

If multiple receivers are available it is possible to tune one receiver to the chosen common control channel to avoid the *multi-channel hidden node problem*. This problem occurs if the channel usage of neighboring nodes is not known and nodes choose to transmit on a busy channel, and furthermore, use a transceiver to carry out data transmissions on different channels [58], [69], [158], [176], [177]. Present commercial sensor nodes have only one transceiver which makes multi-channel MAC protocols that require multiple receivers impractical for the time being.

In general, suitable contention-based multi-channel MAC protocols for WSNs can be further divided into three main classes: namely split phase, periodic hopping, and dedicated control channel. Moreover, protocols in the periodic hopping class can be further divided into common hopping and parallel rendezvous approaches. In all of these cases reservation and negotiation is based on exchanging Request to Send (RTS) and Clear to Send (CTS) messages similarly as in IEEE 802.11. In split phase based

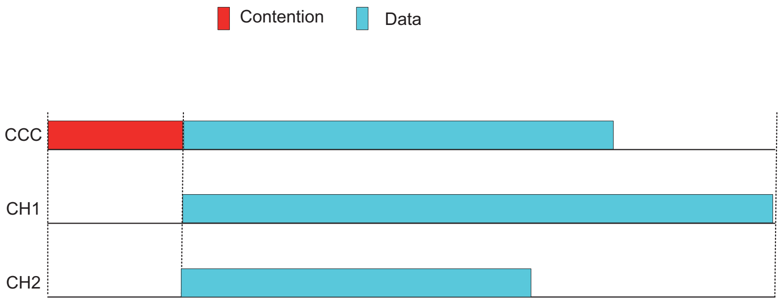


Figure 2.2. General operation of split phase approaches.

random access approaches the operation is divided into two parts. First, during the contention period nodes reserve resources on the chosen common control channel, and afterwards, data transmissions take place during the data period [24], [145], [168].

Operation principles of split phase approaches are presented in Figure 2.2. From the energy consumption point of view, split phase approaches are beneficial since if a node has not negotiated any transmissions during a contention period, it may sleep during the next data period. Even so, the weak point is that in case of irregular packet generation, delays grow substantially since if a packet is generated during the data period it has to be delayed at least until the end of the next contention period. In [156], a similar MAC scheme was proposed for CR networks.

The basic idea behind common hopping approaches is to use periodic channel hopping on every channel in order to avoid availability and congestion problems of the common control channel [159], [160], [161]. All nodes follow the same, predetermined hopping pattern. Figure 2.3 illustrates the basic operation of common hopping approaches. If a node wants to transmit a packet, it sends a RTS message on the current channel to which the receiver responds with a CTS message. Then, the data transmission takes place on the same channel. Since this approach is not energy efficient, it was extended in [74] to be more suitable for WSNs by carrying out channel hopping only in case of congestion. Synchronized MAC (SYN-MAC) [78] is an example of a CR MAC protocol which uses the common hopping approach.

Furthermore, the fundamental concept of parallel rendezvous approaches is that all the nodes employ individual hopping patterns. In McMAC

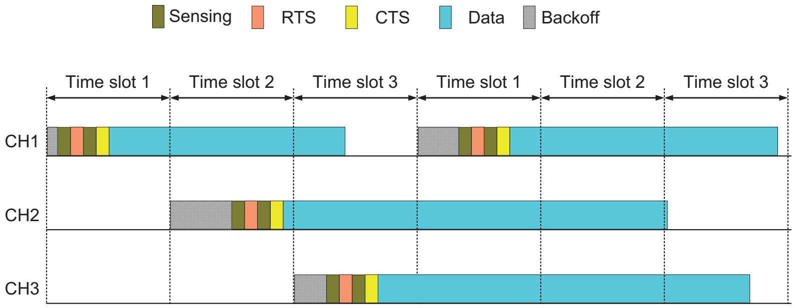


Figure 2.3. General operation of common hopping approaches.

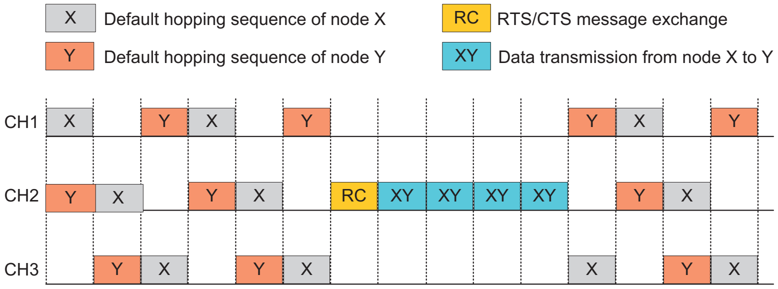


Figure 2.4. Functioning principles of McMAC.

[145], if a node wants to transmit a packet, the node tunes onto the receiver's hopping pattern and the RTS/CTS message exchange and data transmission are carried out on the receiver's current channel. Operation principles of McMAC are demonstrated in Figure 2.4. Other protocols which employ a similar channel hopping structure can be found from [16] and [117]. In the context of CR networks, the protocol presented in [70] was designed by using McMAC as the foundation.

Single transceiver dedicated control channel schemes assign one channel as the Common Control Channel (CCC). Channel reservations are carried out on the chosen CCC using RTS/CTS handshakes while data transmissions take place on the other channels. In [84], the basic operation of IEEE 802.11 was extended for multiple channels by simply allocating data transmissions to different channels. However, the multi-channel hidden node problem is completely ignored in the design. A protocol which considers the multi-channel hidden node problem in this class is Coopera-

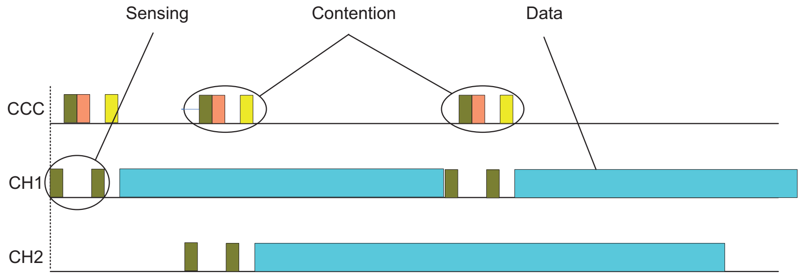


Figure 2.5. Functioning principles of G-McMAC.

tive Asynchronous Multi-Channel MAC (CAM-MAC) [90]. CAM-MAC requires all neighbors that hear a resource request message to verify availability of the proposed data channel. Thus, channel reservations consume a significant amount of resources. Due to the high number of messages during the contention and additional delay, CAM-MAC is infeasible for resource constrained WSNs. A dedicated control channel scheme for CR networks was presented in [150]. However, the protocol requires two (or more) transceivers.

The proposed G-McMAC protocol belongs to the class of dedicated control channel algorithms. While it resolves the multi-channel hidden node problem, it uses only a small amount of resources for channel reservations. Furthermore, G-McMAC is efficient with respect to delay and thus suitable for delay-sensitive WSN applications. The operation principles of G-McMAC are shown in Figure 2.5 as an example of the dedicated control channel approach. Contention takes place on the CCC and data transmissions are carried out on the data channels after sensing the availability of the desired channel. A more detailed description of the operations of G-McMAC are given in Section 3.1. In this scheme nodes can also reserve resources for periodic data transmissions and therefore G-McMAC is considered to be a hybrid multi-channel MAC protocol.

2.1.3 Performance of MAC Protocols

For the case of single-channel systems, the performances of various MAC approaches have been investigated by considering both throughput and delay. Single channel systems were first studied by Kleinrock and Tobagi

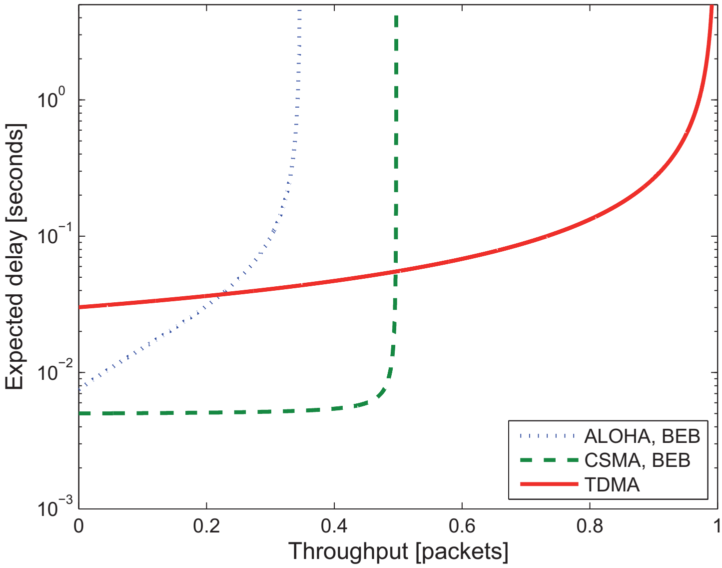


Figure 2.6. Throughput-delay characteristics of TDMA, CSMA, and ALOHA [71].

in [76] where the authors developed equations for delays and throughputs of CSMA and ALOHA using the busy period analysis method. Later on delay distributions of slotted ALOHA and CSMA systems were derived in [180] for different retransmission methods. The operation of single-channel IEEE 802.11 systems was evaluated in [20] comprehensively using a Markov chain model to investigate the impact of backoff window sizes on performance. Markov chains have been used to analyze the performance of IEEE 802.15.4 networks as well. For example, in [114], [101], [112] the operation of single-hop IEEE 802.15.4 systems was investigated with respect to reliability, delay, throughput, and energy consumption while end-to-end reliability in multi-hop networks was studied in [35].

A performance comparison of TDMA, CSMA, and ALOHA has been carried out in [71] by considering the throughput-delay characteristics of the protocols under Poisson traffic. The results are shown in Figure 2.6 where the expected delay is plotted as a function of throughput for each protocol. As the figure demonstrates, CSMA achieves the lowest delay in case of low network load compared to other protocols. Even though TDMA induces high delays with low load, it provides the largest maximum throughput. The reason for this is that with low loads the inflexible frame structure of TDMA causes unnecessary delays since a time slot is allocated for each link even though there would be no traffic. On the other hand, with

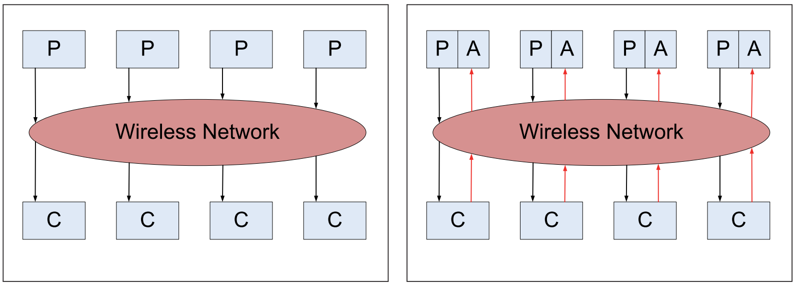
CSMA the probability of collisions grows as the network load increases and hence, TDMA achieves better performance with high loads.

The performance of multi-channel MAC approaches has not been studied as widely but an analysis of different multi-channel protocols in a single collision domain was presented in [102] by performing theoretical analyses and simulations with respect to throughput and delay in saturated traffic conditions. Results show that parallel rendezvous approaches outperform common hopping and split phase approaches in a single collision domain. However, parallel rendezvous approaches are unable to neither dynamically adjust to changes in the radio environment since the hopping patterns are predetermined nor allow sleeping. The same argument applies to common hopping approaches as well.

The difference in performance between common hopping and parallel rendezvous approaches is due to the fact that after a transmission the channel can be immediately reused in parallel rendezvous approaches while in common hopping approaches the channel cannot be reused until the hopping cycle reaches this particular channel again. The main problem with split phase based schemes is that a fixed part of the frame cycle is reserved for resource negotiations which causes throughput degradation and incurs additional delay. If a packet is generated during a data period, it has to wait at least until the beginning of the next data period to be sent.

2.1.4 Conclusions

The most common single and multi-channel MAC protocols suitable for WSNs were reviewed in this subsection. G-McMAC, which is presented in Publication I, was designed by taking into account the requirements of WSN applications. By minimizing access delays G-McMAC enables fast data delivery which is of significant importance for many WSN applications. Furthermore, since the performance of different multi-channel MAC approaches was carried out in [102] by considering only saturated traffic conditions, it is important to investigate how these MAC protocols perform in case of irregular packet generation. This is done in Publication II by comparing the performance of different multi-channel MAC approaches for the case of Poisson packet arrivals.



(a) Networked estimation architecture. **(b)** Networked control architecture.

Figure 2.7. Estimation and control over a wireless network (P: Plant; C: Controller; A: Actuator).

2.2 Networked Control Systems

In Networked Control Systems (NCSs) sensor nodes gather data in a distributed manner and then transmit the measured information to a controller via a shared medium. Controllers make decisions based on the received information and possibly give commands to actuators. Finally, actuators carry out the required operations if necessary. NCSs can be divided into two categories based on operation principles. In networked estimation applications the state of a remote plant or object is estimated based on the measurements collected from sensors. Whereas, control applications include additional feedback loops which are used to transmit commands to actuators.

Figure 2.7 illustrates the difference between networked estimation and control applications over a wireless network setup. In both cases measurement data from plants are sent to a controller using a wireless network. This is represented by black arrows in the figure. However, control applications include additional feedback loops and these are represented by red arrows in the figure. It is also possible to have a control system where the feedback loop does not use the same wireless network, e.g., controllers and actuators may be co-located.

Wireless communications offer novel opportunities for NCS applications due to low installation costs, rapid deployment and flexibility. Wireless networks also enable monitoring in locations where the deployment of wired systems would be extremely difficult such as jungles or hostile environments. Nevertheless, a wireless network introduces challenges as well. Research questions on NCSs are related to packet drops, delay variations, and limited throughput [17], [104], [133]. Restricted resources of low-cost wireless devices, such as limited energy and processing power, characterize the performance of wireless NCSs as well.

The ISA 100 committee has defined five different usage classes of wireless automation. These classes are presented in Table 2.1 [66]. Importance of message timeliness increases while moving from Class 5 to Class 0, i.e., the most delay-sensitive class is Class 0. The applications considered in this thesis belong to the following classes. The crane control system in Publication I is very delay-sensitive and performs critical emergency actions. Hence, it is a safety application of Class 0. The other applications covered in Publication I are less time-sensitive and can be considered as Class 5 applications. Moreover, wireless control loops studied in Publication III form closed loop control systems which fall into the Classes 2 and 3. Finally, the target tracking application in Publication IV is a monitoring application which has short-term operational consequences and hence, it belongs to Class 4.

Table 2.1. ISA100 Usage Classes [66].

Category	Class	Application	Description
Safety	0	Emergency action	Always critical
Control	1	Closed loop control, regulatory	Often critical
Control	2	Closed loop control, supervisory	Usually non-critical
Control	3	Open loop control	Human in the loop
Monitoring	4	Alerting	Short-term operational consequence
Monitoring	5	Logging and downloading/uploading	No direct operational consequence

In [54] a comprehensive survey of NCSs from the perspective of control theory is presented. Since the focus of this thesis is on the communication aspect of the system, where NCSs are merely one possible application scenario for multi-channel wireless communication networks, only the most common solutions from the automation perspective are discussed in this section.

2.2.1 Networked Estimation

Kalman filters are widely used in different estimation applications to improve estimation performance in case of measurement and process in-accuracies. In fact, the Kalman filter is the optimum estimator for the case of linear dynamic systems with Gaussian noise [139]. Possible usage scenarios for Kalman filters include, for example, target tracking [124], biomedical systems [49], and engine health estimation [140]. Conventional Kalman filter theory does not take into account the possibility of missing samples due to packet losses. Instead, periodic estimation (measurement) updates are required. Packet loss, especially in wireless systems may be due to varying channel conditions. Also, when contention-based MAC protocols are used, large and unexpected delays may cause problems. This implies that the Kalman filter has to operate under random sample losses.

Due to the high interest in networked estimation methods, the traditional linear Kalman filtering problem has already been extended to cover possible measurement losses in [141] for the case of single-channel systems. Furthermore, the special case of two separate communication channels was studied in [89] while the case for multiple channels was investigated in [48]. In [89] and [48] packet losses were modeled with independent, identically distributed (i.i.d.) random variables and by assuming that the packet loss process follows the Bernoulli distribution. However, it should be noted that in practice, packet losses may become correlated, e.g., in industrial environments [172]. This has been taken into account in [10] by studying networked estimation for the case of correlated packet losses.

Naturally, the amount of lost packets due to collisions is smaller if less packets are sent. It is possible to reduce the communication load of a network by processing the measured information locally. Instead of transmitting raw data, sensors can make a decision whether or not the measured information should be transmitted, i.e., whether the data are worth sending. An example of this kind of approach is the *send-on-delta* concept [99]. In this strategy, measurement information is only sent when the current measurement value has deviated from the previously transmitted value by some threshold value. Hence, sensor nodes do not transmit measurement information while measured values remain within a certain interval and therefore communication loads are reduced.

In this thesis the focus is on contention-based MAC protocols since these are preferred over TDMA-based solutions due to their simplicity and flexibility of use in many applications. For example, the send-on-delta method generates bursty traffic that cannot be efficiently handled in scheduled systems. In contention-based communications systems, the main source of delay uncertainty is due to MAC procedures. This has motivated researchers to study the impact of different MAC protocols on the performance of networked estimation in single-channel networks. Networked estimation under contention-based media access in single-channel communication systems was studied in [118] by considering slotted ALOHA as the media access mechanism. In the paper a heuristic approach to calculate the channel access rate was presented and the authors demonstrated the relationship between the length of the sampling interval and packet loss rate. Moreover, the joint impact of sampling rate and network size on the estimation performance was analyzed.

Afterwards, this work was extended in [119] by studying geometrically and uniformly distributed waiting times such as those used in slotted ALOHA and CSMA, respectively. Performance of networked estimation in case of synchronized and independent sensors was evaluated by considering both of these approaches. The results show that the lowest packet loss probabilities are achieved by using independent sensors together with uniformly distributed waiting times. Consequently, the performance of networked estimation is better for this case as well when compared to other combinations. However, for optimal estimation performance the length of the sampling period needs to be carefully chosen.

2.2.2 Networked Control

Since a communication network in the middle of a control loop causes variable delays, the control system cannot be considered as time-invariant from the perspective of control theory [109]. This is especially a problem in wireless NCSs and the design of robust controllers is an important topic since the proper operation of the controller in case of random feedback delay and packet losses has to be ensured. In general, the challenges created by delay and delay variations are of significant importance in various contexts in wireless NCSs, such as when studying the stability of NCSs [186] or designing and tuning controllers [42].

Design of the communication network for attaining optimal control performance was studied in [87] by focusing on link layer design trade-offs. In [87] the considered scenario was such that the communication between the sensors and the controller was wireless while the controller and actuator were co-located. Afterwards, this work was extended to cover purely wireless systems [88].

Different wireless systems employ different MAC schemes and therefore their impact on control performance varies as well. Due to this, it is important to evaluate the performance of the chosen controller by considering potential wireless systems. The performance of different single-channel MAC schemes in NCSs has been studied in [86]. In this paper all sensors used the same sampling period and event-based applications were ignored. Hence, polling and TDMA schemes, which are collision-free, outperformed contention-based approaches as expected.

Moreover, in [121] the focus was on random access methods and a performance comparison between three different MAC classes (static, dynamic, adaptive) was performed using the Linear Quadratic Gaussian (LQG) cost function to measure the increase in cost due to shared spectrum. In the paper, protocols with a fixed channel access probability are referred to as *static*. Access protocols which do not take into account the information in packets but consider their transmission history are designated as *dynamic*. Random access schemes that modify their operations based on data and possibly transmission history are called *adaptive*. The results show that the designed adaptive MAC protocol achieves the best performance.

Since IEEE 802.15.4 networks are widely used in WSNs, it is natural that the utilization of such networks as a part of NCSs has already been studied. This was done in [113] where the impact of IEEE 802.15.4 systems on control applications was investigated by focusing on delay. However, the results do not explicilty demonstrate how the choice of communication network parameters affects the control performance and only the impact of the number of nodes on delay is presented.

2.2.3 Conclusions

In this subsection the most relevant results of NCSs from the MAC perspective were discussed. Although multi-channel communication systems are an alluring technology for improving the performance of various applications, the author concludes that none of the previous studies have considered multi-channel communications nor the relationship between communication and control parameters in such systems. The impact of multi-channel communication systems on different applications should be studied in detail since it is of significant importance to understand the interdependencies between the communication and application parameters. Thus, in Publication III and Publication IV the performance of wireless automation and target tracking applications in multi-channel communication networks are investigated, respectively.

2.3 Time Synchronization in WSNs

Time synchronization plays a crucial role in various WSN applications. Precise time synchronization has been identified as one of the most important design objectives, e.g., in industrial automation applications [51]. Accurate time synchronization is required in such applications in order to achieve predictable data collection, precise control, and reliable event logging [26]. Another promising application for WSNs is structural health monitoring which requires simultaneous vibration measurements [162]. The impact of synchronization errors on damage detection in structures was studied in [83] where the authors showed that even small timing misaligments cause time shifts in sensor data which lead to problems in shape reconstruction. Furthermore, in [21] it was inferred that precise time synchronization is essential for carrying out reliable modal analysis in structural health monitoring. Time synchronization is mandatory for other applications as well, such as detection and tracking of various objects.

The main task of WSNs is to gather data which is then combined at the sink to form an overall picture. Without a common time base, data fusion will yield incorrect results as the chronological order of events being reported from the different nodes cannot be determined. This is particularly important in movement tracking and localization [142]. Time synchronization is also the key for successful implementation of sleep schedules, i.e., nodes can be put to sleep in order to avoid excess consumption of power, which form the foundation of many energy conservation schemes [11]. For example, without time synchronization end-to-end delays cannot be measured.

Synchronization in communication systems includes physical layer synchronization and network time synchronization. Physical layer synchronization is required for successful transmissions between two radios. However, physical layer synchronization offers only phase synchronization between two radios and therefore does not provide global time synchronization across entire WSNs. In this thesis the focus is on providing network-wide time synchronization.

2.3.1 Time Synchronization and Clock Model

The motivation for creating efficient synchronization methods is due to the potential of exploiting the cheap, low quality clocks that are available in network elements. Indeed, by using high quality oscillators in every sensor, the demand on synchronization could be relaxed. Nevertheless, cost efficiency is one of the most important design aspects of sensor nodes as the number of nodes in some applications could be enormous which means that the used oscillators should be as inexpensive as possible in order to reduce total production costs of WSNs. Therefore, a trade-off between economical and engineering aspects is required and the purpose of synchronization methods is to compensate for the performance impairments of low quality clocks. Generally, oscillators are affected by the following factors [151]:

- *Temperature:* fluctuations in temperature lead to oscillator drift.

- *Frequency noise:* instabilities of clock crystals cause frequency noise.

- *Clock glitches:* hardware and software abnormalities may create sudden jumps in time.

The behavior of a clock can be modeled in terms of offset Θ, skew θ and drift γ. A general model of a clock can be given by comparing it to an "ideal" clock. Offset indicates the absolute difference between the two clocks at time t while the skew denotes the difference between the speeds of the two clocks. Finally, the rate of change of the clocks' speed is called the drift. The clock model can be represented as a function of time as follows [138]

$$H(t) = \Theta + \theta t + \gamma t^2 + ... \tag{2.1}$$

In Figure 2.8 the impact of clock skew and the purpose of time synchronization are demonstrated. Two nodes with time-varying clock skews are synchronized periodically. Node A's clock skew is denoted by θ_A and Node B's clock skew is θ_B. The ideal clock follows real time, i.e., it has the correct time. At the beginning, all nodes are perfectly synchronized but

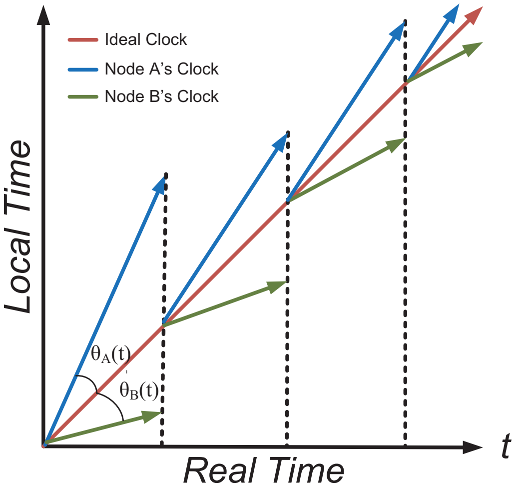


Figure 2.8. Demonstration of clock skew and time synchronization.

after some time Node A's and B's clocks have deviated from the ideal time due to their respective clock skews. By performing time synchronization, Node A's and B's clocks are synchronized to the reference time. However, after synchronization, Node A's and B's clocks start to deviate from the reference time again and need to be synchronized again at some future point in time.

The situation presented in Figure 2.8 depicts a theoretical case where the nodes' clocks achieve the exact time after synchronization, i.e., the nodes are perfectly synchronized. However, in WSNs perfect time synchronization cannot be achieved in practice. The main problem in achieving accurate synchronization is the non-determinismic nature of the different parts of the communication system. Precise time synchronization would be indeed easier to achieve without the following latencies induced by the communication path [39]:

- *Send Time:* at the sender side, the message must be built and processed.

- *Access Time:* when the message is ready for transmission it possibly has to wait for an uncertain amount of time in order to get permission for accessing the transmission media.

- *Transmission Time:* message transmission takes time depending on the length of the message and the capacity of the radio link.

- *Propagation Time:* the wireless communication path is not fixed and therefore the time that different messages travel may not be equivalent.

- *Reception Time:* the receiver needs some time to receive the entire message. Equivalent to transmission time.

- *Receive Time:* at the receiver side, the message must be encoded and processed.

Send times can be minimized by time stamping messages as close to the hardware level as possible. Similarly, the procedure should be repeated at the receiver side as well in order to mitigate receive times. Transmission and reception times depend only on packet lengths and achievable bit rates and it is therefore possible to subtract these values from the overall delay. In contention-based systems, access delays may vary significantly especially in case of congestion while the propagation time is a physical attribute caused by the distance between nodes. Variable delays in radio communication systems have significant impact on time synchronization accuracy making it difficult to achieve precise synchronization between nodes. Even though some of these delays can be removed, the main problem is that many of these latencies are unpredictable.

2.3.2 Time Synchronization Protocols

Network Time Protocol (NTP) [98] has been widely used in the Internet for time synchronization and can provide an accuracy measured in milliseconds. However, WSNs require stricter time synchronization for them to operate efficiently and must cater to the specific timing needs of various applications. Moreover, NTP is not designed for rapidly deployable distributed wireless networks and requires a predefined hierarchy where low quality clocks synchronize to higher quality clocks. This is usually not the case in WSNs since nodes typically have similar clocks and no predefined assumptions on network hierarchy can be made.

On the other hand, Global Positioning System (GPS) can provide very accurate timing information [92]. However, GPS is impractical for WSNs since it requires specific receivers which are expensive compared with the overall price of wireless sensor nodes. Furthermore, GPS may suffer from availability problems due to failure, blockage, or jamming, and requires a satellite connection which means that it will not function well indoors without a relay station [132]. Even though these issues could be solved, the power consumption of GPS receivers makes it an impractical solution for wireless sensor networks in general [40].

The Institute of Electrical and Electronics Engineers (IEEE) has standardized a time synchronization protocol for networked measurement and control systems, named Precision Time Protocol (PTP) [59]. The purpose of the protocol is to fill the gap between NTP and GPS so that sub-microsecond accuracies can be achieved with lower costs than with GPS. Precise time synchronization is achieved by using additional synchronization messages which increases the consumption of network resources. Even though the suitability of PTP for WSNs is still an open question, a few wireless PTP implementations already exist [27], [72]. The results imply that by utilizing PTP it is possible to achieve sub-microsecond time synchronization accuracies over wireless links as well, however, PTP may be infeasible for resource-constrained WSNs due to the large signaling overhead.

Time synchronization in Mobile Ad Hoc Networks (MANETs) was studied in [127]. The proposed algorithm calculates the time difference between the transmitter and receiver so that time stamps from the transmitter can be mapped to correspond to the receiver's clock. Consequently, network-wide time synchronization is not provided and only time stamp transformation is carried out. The algorithm may be useful for some applications which do not require a global time scale, however, in many WSN applications it is very important to create a network-wide understanding of time, e.g., due to data fusion requirements.

Time synchronization in wireless sensor networks has been widely studied and countless protocols have been proposed for such systems during the past decade. Since time synchronization in WSNs is a large topic and a suitable topic for a Ph.D. thesis in itself, see, e.g., [41] and [4], it is not possible to review all the work done in this field in this thesis. Thus, the author would like to direct an interested reader to refer to [152] and [178] for more information. The most important research work carried out in this field is now presented.

It should be noted that the focus here is on time synchronization. Therefore, protocols that provide only phase synchronization are not considered. For example, the protocols presented in [56] and [183] adopt a synchronization method used by biological agents and synchronize nodes by periodically sending pulses. Such approaches offer only phase synchronization, similar to synchronously flashing fireflies, but no time synchronization since time stamps are never received nor transmitted.

Time synchronization approaches in WSNs can be divided into three categories depending on the nature of their operation [178]:

- *Two-way message exchange:* in this approach timing messages are exchanged between two nodes, i.e., master and slave nodes.
- *Receiver-receiver synchronization:* in this approach slave nodes are synchronized to each other but not to the master node.
- *One-way message dissemination:* in this approach only broadcast messages are transmitted by a master.

Timing-sync Protocol for Sensor Networks (TPSN) [47] is a seminal protocol in the category of two-way timing message exhange. TPSN utilizes classical two-way synchronization between a master and slave node. At the beginning, synchronization hierarchy is first formed and then masters and slaves exchange messages periodically to achieve time synchronization. Other protocols that exploit similar messaging include Tiny-sync, Mini-sync [137], and Lightweight Tree-based Synchronization (LTS) [165].

Additionally, an interesting approach in this class is Pairwise Broadcast Synchronization (PBS) [110]. PBS was designed to minimize energy consumption of nodes during the synchronization process. The innovative idea behind this approach is that multiple nodes can exploit timing information they overhear during the synchronization process and therefore the amount of messages required for synchronizing the network is minimized. Time stamps are exchanged between two "super nodes" (one master and one slave) and all other nodes that can hear both of these messages synchronize according to this message exchange.

Even though it was shown that PBS performs much better than TPSN in terms of energy consumption, PBS introduces additional timing errors due to the additional synchronization path between receivers. Hence, this scheme is important in order to minimize the number of synchronization messages. However, two-way synchronization between a master and its slave nodes should still be performed to achieve highest accuracy. This work was extended in [111] to cover multicluster networks as well but the same synchronization accuracy problem remains.

Reference Broadcast Synchronization (RBS), introduced in [39], exploits the receiver-receiver synchronization approach. In RBS, all the receivers time stamp a synchronization packet from the same transmitter individually and then exchange receive time stamps with neighbors. This scheme offers only relative time synchronization among neighboring receivers, not time synchronization with the transmitter. Moreover, several one-way time synchronization message dissemination algorithms for WSNs have been presented. For example, μ-Sync [91], Flooding Time Synchronization Protocol (FTSP) [93], and Time Diffusion Protocol (TDP) [151] all exploit one-way broadcast messaging between masters and slaves.

Despite of all the proposed WSN time synchronization protocols, utilization of multiple channels in the context of network-wide time synchronization in WSNs has not been studied previously, even though multi-channel wireless systems in general are continuously attracting more attention in the research community. For instance, local time synchronization using multiple channels has already been considered in [143] where the authors examined parallel rendezvous-based multi-channel MAC approaches and introduced a synchronization protocol to synchronize one hop neighbor pairs in time. Nevertheless, this approach does not provide network-wide time synchronization and therefore the method in [143] is not feasible for many WSN applications.

2.3.3 Conclusions

In summary, even though many time synchronization protocols have been designed for various WSN applications to provide network-wide time synchronization, none of them exploit multiple frequency channels. The full capacity and advantages of multi-channel WSNs remain untapped. By using multiple bands for synchronization, the convergence time of synchronization processes can be reduced. Therefore, a niche for a new time synchronization protocol such as the one presented clearly exists. This topic is covered in Publications V and VI where a novel multi-channel time synchronization protocol is presented and analyzed.

2.4 Timing & Sensing in Cognitive Radio Networks

The radio spectrum has been historically rigorously regulated and its usage has been tightly controlled so that only licensed users have been able to have access rights [149]. Due to the continuous increase in demand for different wireless communication applications, the problem of inefficient exploitation of scarce spectrum resources has arised. Several measurement campaigns conducted recently around the world in different terrains, geographical areas, and environments demonstrate the fact that a considerable amount of the licensed parts of the spectrum are rarely occupied.

Spectrum occupancy measurement results show that a significant part of the spectrum is underutilized in USA's urban areas (Chigaco, IL [95]) as well as in rural areas (Riverbend Park, Great Falls, VI [96]). Similar measurement studies from Europe carried out in Paris, France [164] and in Lichtneau, Germany [170] highlight the same problem. Since the same issue with inefficient usage is reported to exist in Asia as well [67], this seems to indicate a world-wide problem. Furthermore, in [171] the difference between indoor and outdoor scenarios was measured. Naturally, received power levels are smaller indoors indicating that there would be more spectrum available than outdoors.

Based on these research works and observations it is evident that a feasible way to exploit occassionally or spatially unused parts of the spectrum should be found. It has been foreseen that Cognitive Radios (CRs) [6] could be the solution that would enable flexible and efficient spectrum usage. The term "cognitive radio" does not have a widely accepted definition yet and it has been used in numerous different meanings [107] after the idea of CR was described in 1999 [100]. In general, the purpose of CRs is to exploit momentarily unused parts of the spectrum opportunistically in order to improve spectrum utilization.

2.4.1 Cognitive Radio Networks

In 2008 the IEEE 1900.1 [60] standard was published which specifies definitions and concepts for dynamic spectrum access. Due to the significant role that the IEEE represents in standardization of communication systems, the IEEE definition of cognitive radio will be used in this thesis. It should be noted that this definition does not include any statement regarding secondary spectrum usage. Accordingly, CRs could be exploited, e.g., on the unlicensed Industrial, Scientific and Medical (ISM) radio band. In [60] the term "“cognitive radio"” is defined as follows:

Cognitive radio is *a type of radio in which communication systems are aware of their environment and internal state and can make decisions about their radio operating behavior based on that information and predefined objectives.*

A similar definition of CR systems has been given by the Radio Communication Sector of the International Telecommunication Union (ITU-R) [68]. The only difference between the CR definitions of ITU-R and IEEE is that in the ITU-R definition an additional statement indicates that CR systems should be able to learn from the obtained results as well.

The general operation of cognitive radios includes spectrum sensing, spectrum management, spectrum mobility, and dynamic spectrum sharing [6]. First, the purpose of spectrum sensing is to observe the radio environment and to find the available, currently unused parts of the spectrum, i.e., to identify *spectrum holes* [53] or *white spaces* [108]. Secondly, users place certain demands on the communication system performance and thus, it is important to select the best usable frequency channels for transmissions which is the task of spectrum management functions. Thirdly, the radio environment may change during the operation or the licensed user may start to transmit on the chosen channel(s), and in that case CR users should vacate the channel as soon as possible. Due to this spectrum mobility management strategies have an important role in providing seamless connections while the CR system switches from one channel to another. Finally, spectrum sharing methods that provide a fair share of the spectrum for each CR user are required as well.

CR spectrum access approaches can be categorized into three classes based on the operation principles [179]: underlay, interweave, and overlay. In the underlay approach secondary users transmit simultaneously with primary users on the same frequencies without interfering the primary system. Such secondary systems use spread spectrum techniques and the interference caused by secondary users is controlled to an acceptable level. In overlay methods as well, secondary users exploit the same spectrum as the primary system at the same time. However, in this approach secondary users have additional information about the primary system and can therefore use part of their transmission power to ensure the proper operation of the primary system under additional interference.

Finally, in the interweave approach, secondary users can access the spectrum only when the primary system is not transmitting, i.e., there will not be simultaneous transmissions of primary and secondary users as in the other approaches. It seems that this latter approach will be implemented first since it is the foundation of the IEEE 802.22 standard [63] which is a standard for Wireless Regional Area Networks (WRANs) operating on white spaces of the TV spectrum.

In the interweave approach it is important to be able to identify whether the primary system is transmitting or not. This can be achieved by listening to the frequency channel using sensing-based methods. On the contrary, it is possible to use geolocation-based systems where information about the spectrum usage is derived from a database. Most likely these two methods will be used in conjunction, if possible, to achieve the best sensing performance. For example, the European Communications Committee (ECC) has considered this option while defining technical requirements for CR systems in [37]. In the context of this thesis, the focus is on evaluating and improving the sensing aspect.

Dynamic spectrum access is beneficial in WSN applications as well. Since regulators in different countries have been working separately in the past, licensed bands for WSNs vary in different regions of the world. As a consequence, most of the WSN systems exploit ISM bands to enable global usage. However, since ISM bands are not exclusively licensed, several applications may use these frequency bands simultaneously. For example, IEEE 802.11 b/g networks may interfere with IEEE 802.15.4 sensor networks and thereby introduce significant coexistence problems for low-power sensor nodes, see [136] and [57] for example. Due to the crowded spectrum, the performance of WSNs deteriorates and reliable communications cannot be guaranteed [148]. Hence, the dynamic selection of used frequency bands would help to avoid interference and ensure proper operation.

In fact, a wireless sensor network using cognitive radio technology has already been defined and the new sensor networking paradigm is referred to as *Cognitive Radio Sensor Network (CRSN)*. The definition of CRSN was given in [5] as follows:

A CRSN is *a distributed network of wireless cognitive radio sensor nodes, which sense event signals and collaboratively communicate their readings dynamically over available spectrum bands in a multihop manner to ultimately satisfy the application-specific requirements.*

Sensors equipped with cognitive radios are aware of their environment and internal state, and can make decisions about their radio operating behavior based on that information and predefined objectives. This enables both more reliable packet delivery and more efficient utilization of scarce spectrum resources.

2.4.2 Spectrum Sensing

Since spectrum sensing is essential in all CR networks to ensure proper protection of licensed users or to avoid interfered frequencies, the problem of reliable spectrum sensing should be solved before other issues. Several spectrum sensing algorithms have been designed which have different predefined operation requirements such as whether knowledge about the detected signal is required or not. Furthermore, achievable accuracies and complexities distinguish different sensing algorithms. In fact, accuracy and speed of detection have been identified as the main performance metrics for CR networks [13]. The most common sensing algorithms can be categorized into the following classes based on the principles of detection [23]: energy detector based sensing, cyclostationarity-based sensing, and matched-filtering. Additionally, in [184] waveform-based sensing and radio identification were identified as possible sensing techniques for CR networks.

Energy detectors simply compare the power of the received signal to a threshold and are not therefore able to differentiate between primary user's signal and noise. Energy detectors are the most vulnerable to noise uncertainty which has been shown in [153] and [154] where the Signal to Noise Ratio (SNR) walls of different sensing methods were studied. SNR walls define the limit after which it is impossible to achieve robust detection, i.e., no matter how many samples are collected the performance cannot be improved. The results presented in these papers show that single antenna energy detectors have the highest SNR wall. On the other hand, energy detectors are simple to implement, fast, and do not require any knowledge of the primary user's signal. Furthermore, by using multiple antennas it is possible to improve the performance of energy detection significantly [130].

Cyclostationarity-based detection methods do not require information about the detected signal either. Instead, the periodic behavior of signals is exploited. Even though transmitted data are generally seen as a sta-

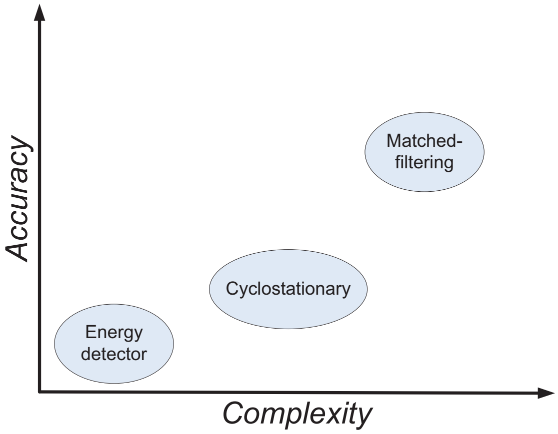


Figure 2.9. Performance of the main sensing methods in CR networks.

tionary random process modulation with sinusoidal carriers, cyclic prefixes or hopping sequences creates cyclostationarity in the received signals. For example, the cyclic properties of Orthogonal Frequency Division Multiplexing (OFDM) signals can be exploited in detection [82].

On the other hand, utilization of the matched-filtering technique requires full knowledge of the signal waveform to be detected. The primary user has to send known pilots with the data which enables secondary users to perform carrier and timing synchronization. Matched filters are essentially optimal detectors and achieve the highest performance. Pilot signals and matched-filtering can be exploited, e.g., to identify TV transmitters and find the white spaces of the TV spectrum [81].

The performance of these most common sensing approaches is summarized in Figure 2.9 [184]. As the figure demonstrates, energy detection outperforms other solutions in terms of simplicity while it has the worst accuracy. Cyclostationary-based sensing gives mediocre performance in terms of accuracy and complexity while matched-filtering yields the best sensing results at the expense of complexity. The selection of the detection algorithm depends on the scenario in question and practical limitations such as hardware resources and the availability of knowledge about the primary users' signals [103]. It seems that, at least in the beginning, energy detection will be used in CR networks since it has been included into the IEEE 802.22 standard [63].

Energy detection was first analyzed in [163] where closed-form solutions for detection and false alarm probabilities were derived for energy detection in the case of unknown deterministic signals. The analysis was extended in [80] to cover signals with a random amplitude. Furthermore, the impact of different fading channels on energy-based detection was studied in [36]. In all of these studies it was assumed that all measured samples experienced similar noise levels.

Furthermore, WSNs can be exploited in regular CR networks as well. In order to realize the benefits of CRs, spectrum awareness is a prerequisite. Typically this is done by cooperative sensing, i.e., all CR nodes in the network share the same quiet period and sense the spectrum simultaneously. For example, in the presence of shadow fading, reliable detection is only possible by fusing sensing results from multiple sensors [129]. WSNs can be used to assist a CR network in sensing by providing information on current spectrum occupancy [97]. This concept, called wireless sensor network aided cognitive radio, has already been studied in an EU funded project entitled SEnsor Network for Dynamic cOgnitive Radio Access (SENDORA) [134]. The project considered the business analysis of such systems while technical aspects were taken into account by studying dynamic spectrum access and resource allocation in these networks. Moreover, a reconfigurable architecture for the WSN aided cognitive radio networks was designed.

2.4.3 Conclusions

The motivation behind and the idea of CR networks were considered in this subsection. The most common spectrum sensing methods were introduced as well. In CR networks multiple available frequency bands may be detected that can be used for data transmission. Therefore, CR MAC protocols are similar to multi-channel MAC protocols designed for ad hoc networks with the exception that in CR MAC protocols some time has to be allocated for spectrum sensing [31], [32]. Thus, the multi-channel time synchronization protocol presented in Publications V and VI are applicable to CR networks as well together with a suitable MAC protocol. In addition to the application specific time synchronization requirements, there is further motivation for time synchronization in distributed CR networks.

In various sensing studies it was assumed that CR nodes are quiet and sense channels at identical times which requires perfect time synchronization. In practice this assumption may not hold since other CR nodes may transmit during the sensing period because of timing errors. The impact of interfering CR nodes on the performance of energy detection is therefore studied in Publication VII. It is shown that nodes should be synchronized in time to achieve good sensing performance. Nevertheless, in some cases it may not be possible to perform accurate time synchronization which motivated the design of a novel interference suppression sheme for distributed CR networks under timing inaccuracy. This method is presented in Publication VIII. The fact that energy detection will be exploited in CR networks, such as in IEEE 802.22 networks [29], was the reasoning behind choosing energy detection as the spectrum sensing technique in these studies.

3. Summary of Publications

In this section the results of the papers included in this thesis are summarized. Publications will be referred to in the text such that an interested reader can find relevant and more detailed information from the publications. In this section only the main results are presented while the publications include the derivations of equations, simulation setups, and results.

3.1 Multi-Channel Communications in Wireless Sensor and Ad Hoc Networks (Publications I & II)

In Publication I a novel multi-channel Media Access Control (MAC) approach designed especially for industrial Wireless Sensor Networks is proposed, entitled Generic Multi-channel MAC protocol (G-McMAC). The performance of G-McMAC is compared with other existing multi-channel MAC approaches in Publication II. Simulation results from an example industrial scenario are presented in Publication I which demonstrate the applicability of G-McMAC for industrial WSN applications.

3.1.1 Generic Multi-Channel MAC

The operation of G-McMAC is divided into two segments: Beacon Period (BP) and Contention plus Data Period (CDP). Figure 3.1 represents the general operation of G-McMAC. BPs are used for distributing routing information, carrying out time synchronization, and exchanging information about channel schedules. Whereas, resource negotiations and data transmissions are performed during CDPs. Beaconing and resource reservations occur on the common control channel.

Each beacon includes the preferred channel list, send time stamp, chan-

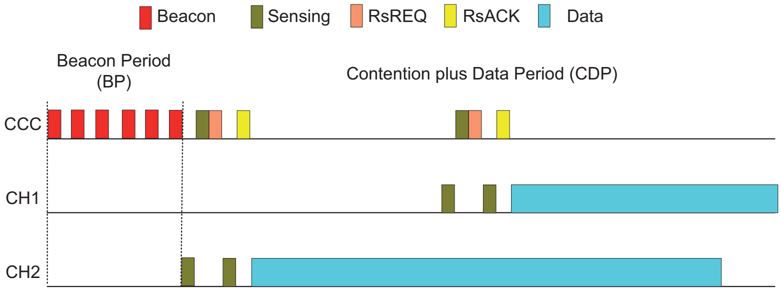


Figure 3.1. Operation of the proposed G-McMAC.

nel schedules, hierarchy level, and length of the BP. Gateway node (GW) resides on level 1 on the synchronization hierarchy and initiates the beaconing process by sending the first beacon. All the receivers synchronize to the time reference provided by the GW and set their level to 2. After this, the nodes on level 2 broadcast beacons as well. Nodes that receive these beacons synchronize themselves and set their level to 3 and so forth. The process is terminated after all the nodes have broadcasted a beacon.

After a node has received beacons from all of its neighbors, it can start the data negotiation process. If a node has a packet to send it first senses the desired channel to acquire the latest channel information, and after this, the node sends a Resource REQuest (RsREQ) message on the Common Control Channel (CCC) to the intended receiver which includes the desired data channel and transmission time. After receiving a RsREQ, the intended receiver senses the desired data channel and responds by sending a Resource ACKnowledment (RsACK) message on the CCC if the channel is suitable. After this, the nodes carry out the data transmission on the chosen channel.

A more detailed description of G-McMAC can be found in Publication I. Briefly stated, the properties of G-McMAC are now summarized. G-McMAC enables coexistence of multiple wireless sensor applications and prioritization of applications. Moreover, it combines routing and time synchronization to improve efficiency. Resource reservations for periodic data and multi-hop communications are supported as well. Finally, G-McMAC adapts dynamically to changes in network topology, performs interference avoidance, and achieves low access delays.

3.1.2 Delay-Throughput Analysis

A performance comparison of different multi-channel MAC approaches is carried out in Publication II by performing a delay-throughput analysis. The examined protocols are G-McMAC, Multi-channel MAC (MMAC) [145], and Synchronized MAC (SYN-MAC) [78]. The length of a time slot in seconds is denoted by τ and packet arrivals are modeled as a Poisson process with a rate of g packets per time slot (packets/τ) which includes both new and retransmitted packets. Packet size T and the size of the backoff window ω are defined in time slots τ. The length of the contention period in SYN-MAC is denoted by $T_s = \omega$.

In the appendices of Publication II the following probabilities are derived for these multi-channel protocols by using the busy period analysis method [126]: P_s is the probability of successful transmission, P_c is the probability of collision, and P_b is the probability that the channel is sensed busy. The probabilites collected from Publication II are presented in Table 3.1.

Table 3.1. Probabilities of the protocols from the busy period analysis without taking into account the finite number of channels.

	G-McMAC	MMAC	SYN-MAC
P_s	$\frac{e^{-g\tau}}{4-3e^{-g\tau}}$	$\frac{e^{-g\tau}}{(3-2\ e^{-g\tau})}$	$\frac{(T_s/T)e^{-g\tau}}{1+(T_s/T)-e^{-g\tau}}$
P_b	$\frac{3\left(1-e^{-g\tau}\right)}{4-3e^{-g\tau}}$	$\frac{2(1-e^{-g\tau})}{(3-2e^{-g\tau})}$	$\frac{1-e^{-g\tau}}{1+(T_s/T)-e^{-g\tau}}$
P_c	$\frac{1-e^{-g\tau}}{4-3e^{-g\tau}}$	$\frac{1-e^{-g\tau}}{(3-2e^{-g\tau})}$	$\frac{(T_s/T)(1-e^{-g\tau})}{1+(T_s/T)-e^{-g\tau}}$

Equations for the throughput and average access delay of these protocols are derived in Publication II. The average access delay of G-McMAC depends on two issues. First, the contention process on the CCC and possible collisions induce some delay. Secondly, if all data channels are occupied an extra delay is added as well. The average access delay is given by

$$\bar{D} = \frac{\tau}{2}\left(\frac{\omega P_s}{1-2(1-P_s)} + \frac{9}{P_s} - \frac{6P_b}{P_s} + 2 - \omega\right), \quad P_s > 0.5. \tag{3.1}$$

Consequently, $P_s > 0.5$ is required to have a finite average delay. Moreover, the throughput of G-McMAC is given by

$$S = gT \cdot \frac{e^{-g\tau}}{4-3e^{-g\tau}} \cdot (1 - P_{occ}), \tag{3.2}$$

where the probability that all channels are occupied is given by the Erlang-

B formula [44]:

$$P_{occ} = \frac{\frac{(gT)^{N-1}}{(N-1)!}}{\sum_{i=0}^{N-1} \frac{(gT)^i}{i!}}, \tag{3.3}$$

and N is the number of channels.

Next, the performance of split phase approaches is studied by using MMAC [145] as an example. The operation of MMAC is divided into two parts which form a cycle. MMAC exploits the Ad hoc Traffic Indication Message (ATIM) windows of IEEE 802.11. In MMAC, channel reservations are conducted during ATIM windows on the CCC. Data transmissions take place on all available channels afterwards. We denote the length of the ATIM window by T_{atim} and the length of the data interval is fitted to the packet size T, both defined in time slots. Thus, the length of one cycle is $T_c = T_{atim} + T$.

In case of MMAC, a node has to wait until the end of an ATIM window even though the initial transmission would be successful before transmitting data. Consequently, on average the initial transmission delay is

$$\bar{D}_0 = \frac{T_{atim}}{2} \cdot \frac{T_{atim}}{T_c} + \left(\frac{T}{2} + T_{atim}\right) \cdot \frac{T}{T_c}. \tag{3.4}$$

If the delay due to CSMA operations during an ATIM window is larger than the length of the ATIM window, or all of the channels are occupied before a node can reserve resources, a packet will be delayed by one cycle. The probability that a node cannot reserve resources during an ATIM window – due to the shortage of data channels and the probability of blocking due to the end of a contention window – are denoted by P^c_{block} and P^d_{block}, respectively. Now, the effect of additional cycles can be formulated as

$$\bar{D}_{block} = (P^d_{block} + P^c_{block} - P^d_{block} \cdot P^c_{block})T_c, \tag{3.5}$$

and thus, the average access delay of MMAC is given by

$$\bar{D} = \bar{D}_0 + \bar{D}_{block}, \tag{3.6}$$

and the throughput is

$$S = g_a T \cdot \frac{e^{-g_a \tau}}{(3 - 2\, e^{-g_a \tau})} \cdot (1 - (P^c_{block} + P^d_{block})), \tag{3.7}$$

where g_a is the arrival rate of MMAC which is scaled upwards since contention for resources occurs only during ATIM windows.

SYN-MAC [78] is used as an example of common hopping approaches and the same delay-throughput analysis applies to parallel rendezvous

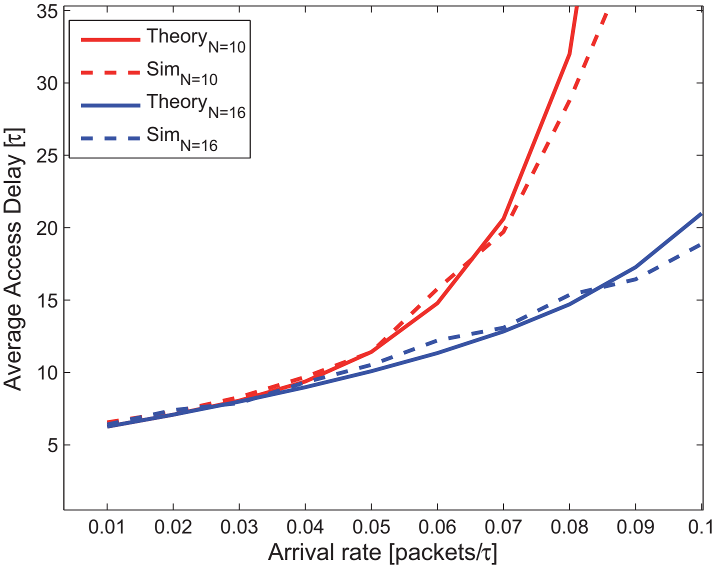


Figure 3.2. Theoretical and simulated results for average access delay of G-McMAC (T=100, ω=32).

schemes as well. SYN-MAC exploits periodic hopping and resource reservations can be performed only for the current channel to avoid the multi-channel hidden node problem. Therefore, the performance of SYN-MAC can be estimated in a likewise manner to single-channel systems by reducing the arrival rate of packets due to the utilization of multiple channels at identical times.

In SYN-MAC the minimum average latency of a successful transmission is given by

$$\bar{D}_0 = T_s + \frac{T_s}{2}, \tag{3.8}$$

and then, the average access delay is

$$\bar{D} = T_s \left(\frac{2 + P_s}{P_s} \right), \quad P_s > 0, \tag{3.9}$$

while the throughput is

$$S = g_s T \cdot \frac{(T_s/T)e^{-g_s \tau}}{1 + (T_s/T) - e^{-g_s \tau}}, \tag{3.10}$$

where g_s is the scaled arrival rate corresponding to the operations of SYN-MAC.

The correctness of these theoretical derivations has been verified by simulations and the results are reported in Publication II. As an example, Figure 3.2 illustrates the theoretical and simulated results for the average access delay of G-McMAC as a function of arrival rate. It can be

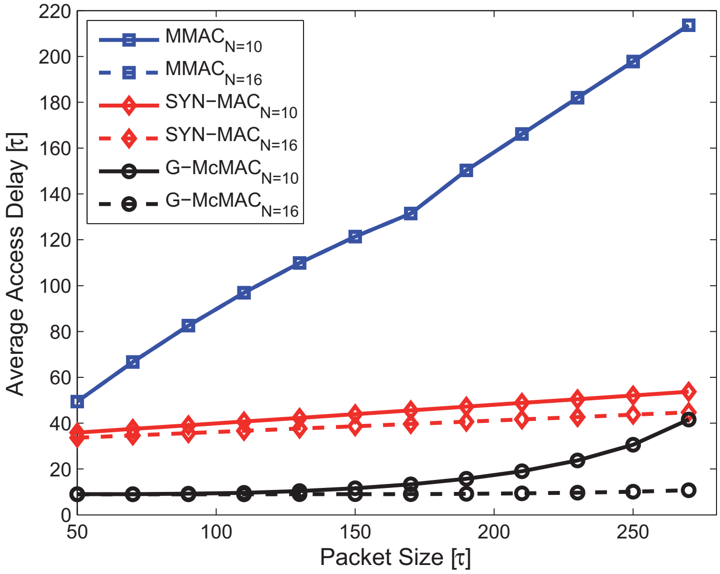


Figure 3.3. Average access delays as a function of packet size (g=0.04).

inferred from the figure that the theoretical derivations match the simulations well.

Results and Analysis

Results for average access delay as a function of packet size are presented in Figure 3.3. In general, G-McMAC offers significantly lower delays than other approaches with small packets regardless of the number of channels. The effect of packet size starts to be visible just before approaching the stability point, which is $T = 300$ while $N = 10$ and $g = 0.04$ for G-McMAC, even though the effect of packet size on the delay is minimal in general. SYN-MAC achieves relatively constant delays with different packet sizes and approaches G-McMAC when the stability point of G-McMAC is approached. Nevertheless, with small packets the difference is remarkable and SYN-MAC introduces over twice as large delays as G-McMAC. Furthermore, the performance of MMAC is already significantly worse with small packet sizes, and access delay increases linearly with packet size. The MMAC curves overlap in this case since the contention period is so small that all channels cannot be used during the data period. In general, the results show that G-McMAC outperforms other protocols with respect to delay regardless of the applied communication parameters while it is stable.

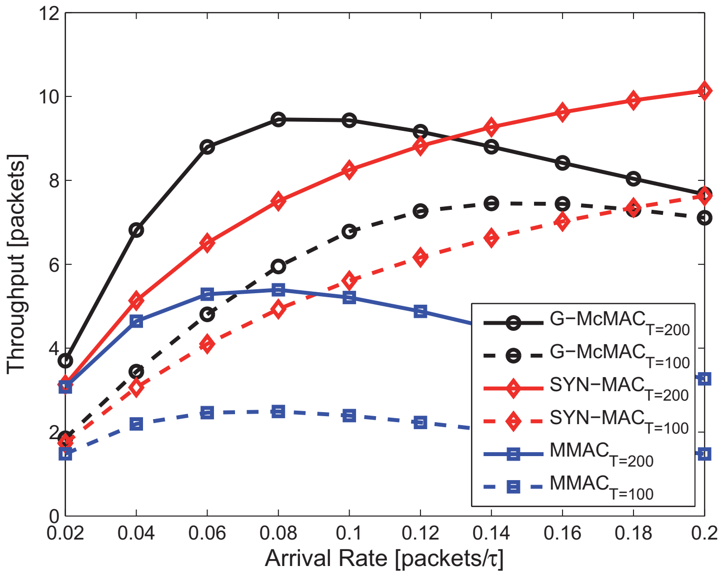


Figure 3.4. Throughput as a function of arrival rate (N=16).

The impact of critical parameters on the throughput of different multichannel MAC approaches was then studied. Figure 3.4 shows the throughputs of the protocols as a function of packet arrival rate for two different packet sizes. For the case of small arrival rates G-McMAC clearly outperforms other protocols. However, the achieved gain depends on the chosen packet size and arrival rate. With these parameters, MMAC provides the smallest throughputs regardless of the arrival rate. On the other hand, SYN-MAC surpasses G-McMAC in terms of throughput eventually when approaching the stability point of G-McMAC. As a conclusion, G-McMAC achieves better throughput than SYN-MAC especially for small or moderate arrival rates. Nevertheless, SYN-MAC offers the highest throughputs in case of high arrival rates and small packets.

When embarking on any wireless communication design, it is essential to understand the operation region of the used MAC protocol to ensure system stability. Figure 3.5 illustrates the delay-throughput curves of MMAC, SYN-MAC, and G-McMAC. Evidently, MMAC performs most poorly since it induces high latencies and becomes unstable when the throughput is low. Moreover, it can be seen from the figure that G-McMAC clearly outperforms SYN-MAC by offering lower delays in general. However, G-McMAC becomes unstable before SYN-MAC. In fact, after passing the stability point of G-McMAC the throughput of SYN-MAC still contin-

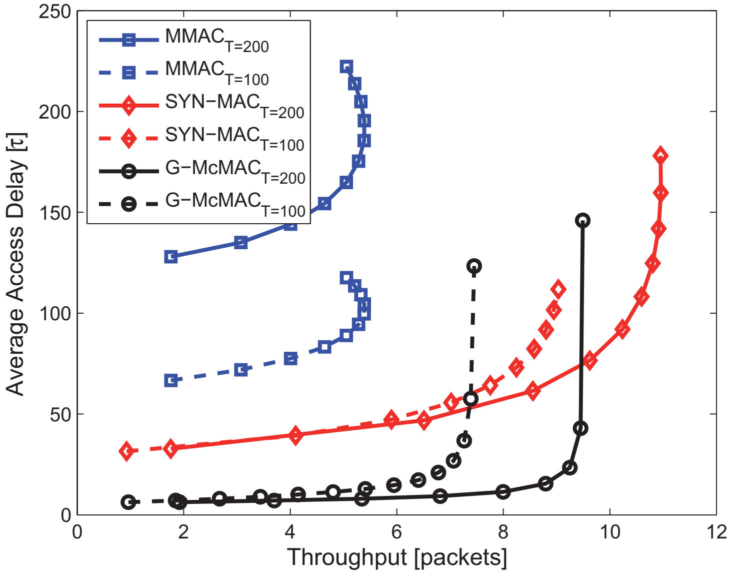


Figure 3.5. Delay as a function of throughput (N=16).

ues to improve. Based on this observation it can be concluded that in order to minimize access delay, G-McMAC should be used. However, if it is important to maximize throughput at the expense of access delays, SYN-MAC should be considered.

The differences between TSMP and G-McMAC can be analyzed by exploiting the performance comparison of TDMA and CSMA presented in Section 2.1.3. TSMP is a multi-channel TDMA protocol while G-McMAC is a multi-channel CSMA protocol. Therefore, their behavior is similar to the corresponding single-channel MAC algorithms and the same conclusions about the performance apply. TSMP achieves higher maximum throughput while G-McMAC provides significantly lower delays in case of intermittent packet arrivals and low network loads.

3.1.3 Simulation Results

G-McMAC was implemented on ns-2 [94]. The coexistence of the following three applications in an industrial environment was considered in the simulations: 1. Crane Control System (CCS), 2. Machine Health Monitoring System (MHMS), and 3. Air Conditioning Unit (ACU). In these simulations, CCS has the role of the primary network and the highest priority while MHMS and ACU are assigned similar secondary priorities,

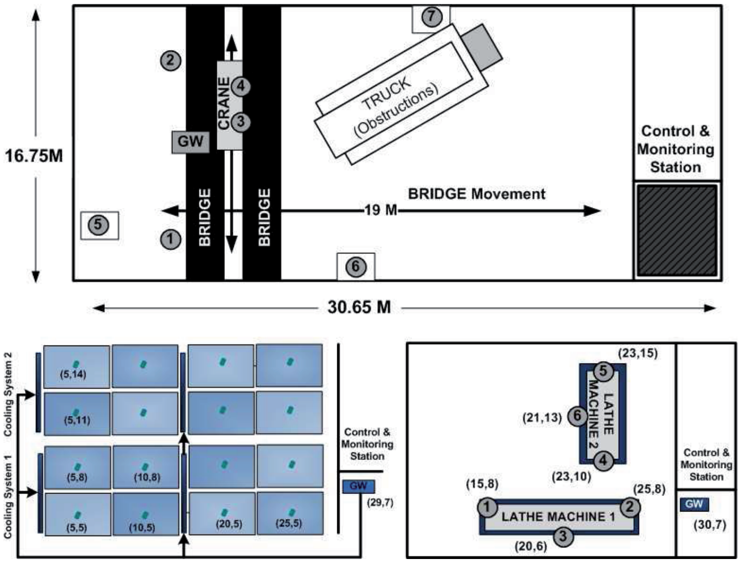
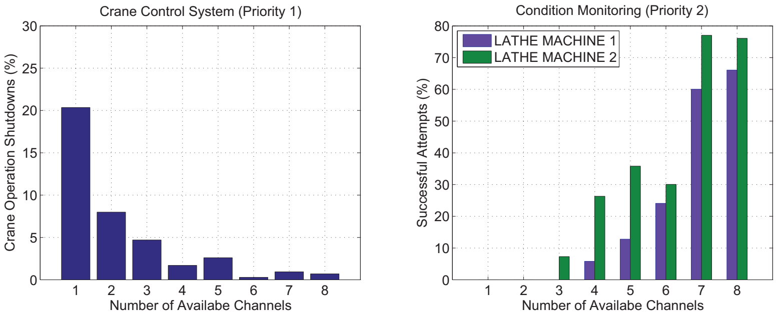


Figure 3.6. Coexistence of three applications in an industrial environment: 1. CCS (top), 2. MHMS (bottom right), and 3. ACU (bottom left). ©2011 IEEE.

i.e., they compete for the resources. Consequently, the communication network should be able to share the resources while ensuring prioritized media access.

Typical communication constraints for CCS include a 500 ms maximum delay bound and the GW should receive packets from all the nodes within this time. Failing to do so results in a noticeable delay and subsequently an emergency stop of the crane. MHMS consists of wireless sensors that are on top of a lathe machine to monitor the integrity of the structure (vibrations). The data sampling frequency is usually high in these kinds of applications and the traffic scenario is a challenging task for G-McMAC since the secondary network demands large resources. The ACU maintains the temperature of the industrial hall at the desired level (21° C). Figure 3.6 illustrates the simulation scenario.

The results shown in Figure 3.7a imply that G-McMAC provides a failure rate of 20 % in case of scarce channel resources for CCS, i.e., crane shutdowns occur with a probability of 20 %. The performance of CCS can be significantly improved by exploiting multi-channel communications since the failure rate is very low (approx. 1 %) with 6-8 available channels. The lower priority MHMS application shows a significant drop in performance for less channels and the performance improves as the number of available channels is increased as well, see Figure 3.7b. On the other hand, for the case of the ACU the performance does not im-



(a) CCS: Operation shutdowns.

(b) MHMS: Successful attempts.

Figure 3.7. G-McMAC: Simulation results. ©2011 IEEE.

prove while the number of channels is increased since MHMS and CCS use most of the resources. Due to the low communication requirement of the ACU, its performance is satisfactory anyway. These simulation results imply that G-McMAC effectively integrates application priority, enables coexistence of various networks, and achieves good performance in case of multiple overlapping WSNs.

Traffic from three non/partial-overlapping IEEE 802.11b systems at different center frequencies has also been considered in the simulations. The results show that the coexistence of IEEE 802.15.4 and IEEE 802.11 networks can be achieved and G-McMAC is able to avoid interference by choosing channels that experience the least interference.

3.2 Exploitation of Multi-Channel Communications in Different Applications (Publications III & IV)

In Publication III the impact of multi-channel communications on wireless automation applications was studied by considering the interdependencies between communication and control parameters. Furthermore, Publication IV deals with networked estimation in multi-channel systems by focusing especially on target tracking applications. Since it has been shown that G-McMAC outperforms other approaches with respect to delay, G-McMAC is investigated in both papers.

3.2.1 Multi-Channel Communications in Wireless Automation

Especially in real-time control systems, large delays and delay variations may have catastrophic consequences by introducing instability in the control system. To implement wireless control systems these issues need to be taken into account. It is therefore essential to understand the relationship between critical communication parameters, such as the number of available channels, packet arrival rate, and packet size, and control system parameters. In Publication III the effect of multi-channel communications along with different communication and automation parameters on the performance of a wireless control system is evaluated.

The Poisson packet arrival model is commonly used to model random, independent message arrivals in communication systems so that packets are generated according to the Poisson distribution. In wireless automation, Poisson distributed traffic arises typically for the case of event-driven systems, unsynchronized sensors, and random sampling. Justification for the use of the Poisson arrival processes in wireless automation is given in Publication III. In the following analysis it is assumed that the packet arrival process follows the Poisson distribution.

To be able to analyze the impact of multi-channel communications on wireless automation applications, the delay distribution of G-McMAC has to be derived. For this, an approximation for the Cumulative Distribution Function (CDF) of delay is derived and the correctness of the approximation is verified by simulations. It is possible to determine an accurate approximation for the delay CDF by using the probability of successful transmission. Delay CDF $F(D)$ is approximated in a piecewise manner as follows.

First, if the initial transmission attempt of a packet is successful, the access delay is $D = D_0 \sim U(5\tau, 6\tau)$. For example, while $T = 100$ and $N = 16$ we get $P_s = 0.86$. After this point, the CDF increases linearly until $D = D_0 + \omega$ is reached. By denoting the number of retransmissions by R it can be stated that between $D_0 \leq D \leq D_0 + \omega$ the delay is dominated by the probabilities $P\{R = 0\}$ and $P\{R = 1\}$. Moreover, while $D = D_0 + \omega \leq D \leq D_0 + 2\omega$ and $D = D_0 + 2\omega \leq D \leq D_0 + 3\omega$, $P\{R \leq 2\}$ and $P\{R \leq 3\}$ dominate, respectively.

By continuing this reasoning, the probability that the delay of a packet

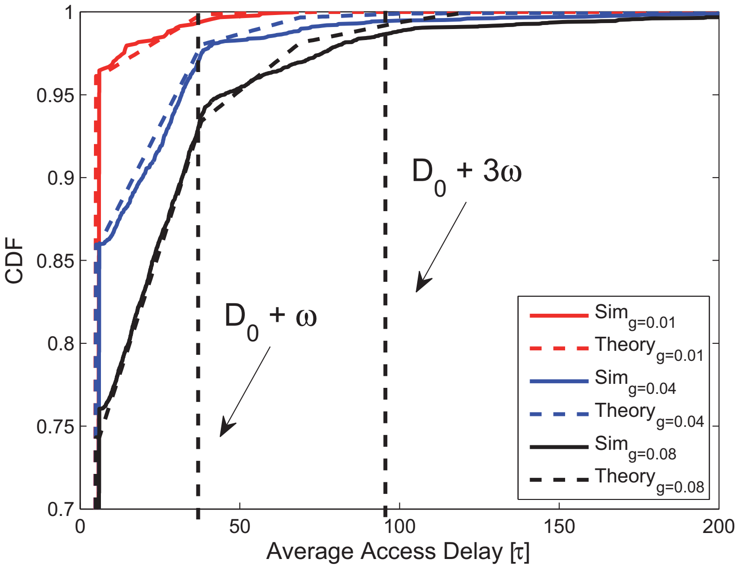


Figure 3.8. CDF of the delay for G-McMAC (T=100, N=16).

is D can be formulated as follows

$$P(D) \approx \begin{cases} P_s, \quad 5 \le D \le 6, \\ (1-P_s)P_s, \quad D_0 \le D \le D_0 + \omega \\ (1-P_s)^2 P_s, \quad D_0 + \omega \le D \le D_0 + 2\omega \\ (1-P_s)^3 P_s, \quad D_0 + 2\omega \le D \le D_0 + 3\omega \\ \vdots \\ (1-P_s)^\rho P_s, \quad D_0 + (\rho-1)\omega \le D \le D_0 + \rho\omega, \end{cases}$$

where ρ is the maximum number of retransmissions. The CDF of a certain delay value is therefore given by

$$F(D) = \sum_{D_i=0}^{D} P(D_i). \tag{3.11}$$

Figure 3.8 shows the results of the approximation together with the simulated results. The difference between the simulated and theoretical curves is small and the results imply that the approximation is accurate, especially when D is small.

A Continuous-time Proportional-Integral-Derivative (PID) controller is used as an example and the gains of the controller are denoted by k_p, k_i, and k_d, respectively. The transfer function of the text book PID controller $C(s)$ is of the form [1]

$$C(s) = k_p + k_i \frac{1}{s} + k_d s, \tag{3.12}$$

where s is the Laplace variable ($s \in \mathbb{C}$).

The impact of delay and delay variation on the performance of the controller can be studied by considering the robustness of the control system. Since a controller designed for the maximum delay does not ensure stability of the closed-loop system [55], delay variations can be taken into account in control system design by exploiting the jitter margin. The latter defines the upper bound of the maximum delay. The jitter margin theorem of Kao and Lincoln [73] defines an upper bound for the delay jitter δ_{max} for which the control loop is guaranteed to be stable

$$\left|\frac{P(j\omega_a)C(j\omega_a)}{1+P(j\omega_a)C(j\omega_a)}\right| < \frac{1}{\delta_{max}\omega_a}, \qquad \forall\omega_a \in [0,\infty] \tag{3.13}$$

where ω_a denotes the angular frequency ($s = j\omega_a$) and $P(j\omega_a)$ is the process transfer function. The upper bound of δ_{max} can then be solved and placed in the form

$$\delta_{max} < \left|\frac{1+P(j\omega_a)C(j\omega_a)}{\omega_a P(j\omega_a)C(j\omega_a)}\right|. \tag{3.14}$$

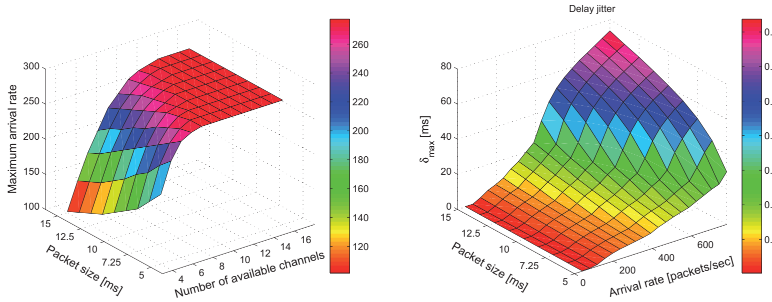
In [43], the following approximation of the relationship between the tuning parameter, delay, and jitter margin for the First Order Lag plus Integrator plus Delay (FOLIPD) process model for the PID controller case was derived as

$$a = \frac{0.9562L}{\delta_{max} + 0.6431L_d}, \tag{3.15}$$

where L_d is the delay constant of the controller and a is a tuning parameter (a-tuning). This can be tuned in many ways, e.g., based on the overshoot criterion, or gain and phase margins. In general, higher a gives better performance.

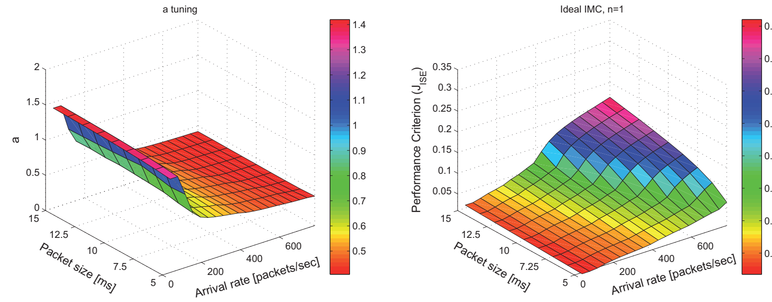
First it was studied how the critical communication parameters should be chosen if the target performance of the control system is determined beforehand. Figure 3.9a illustrates the impact of different communication parameters on performance. The figure shows the expected behavior of the maximum arrival rate growing as the number of available channels is increased or the packet size is decreased. The effect of communication parameters on the jitter margin is depicted in Figure 3.9b where the value of the jitter margin is plotted as a function of arrival rate and packet size. With small packets and low arrival rates, the delay is small which makes the use of small jitter margins possible.

Figure 3.9c shows the effect of communication system perfomance on the tuning parameter. Since an increase in the arrival rate enhances delay, larger jitter margins are needed which leads to performance deterioration of the control system.



(a) Maximum arrival rate.

(b) Jitter margin.



(c) Controller performance (a-tuning).

(d) Controller performance (IMC).

Figure 3.9. Interdependencies between communication and control parameters.

If the exact process model is known, it is possible to determine the perfect controller for that specific process by applying the Internal Model Control (IMC) approach. Next, the impact of disturbances caused by the used communication system on the performance of the IMC controller was studied. In this case the Integral Square Error (ISE) cost function was used as the performance criterion, denoted by J_{ISE}, and it is defined as

$$J_{ISE} = \int_0^{\infty} \left(y_r(t) - y_m(t)\right)^2 dt, \tag{3.16}$$

where y_r is the reference and y_m is the process output.

Results for the ideal closed-loop transfer function are illustrated in Figure 3.9d. From the figure it can be seen that the effect of arrival rate on the performance is more significant than packet size since with low arrival rates the chosen packet size does not affect the performance. When the arrival rate is increased the selection of packet size becomes more important. Nevertheless, in general the performance criterion increases more rapidly as a function of arrival rate than packet size. The results demonstrate the interdependencies between wireless communication and control systems. By properly adjusting the parameters on both sides of the system it is possible to find some middle ground where performance is satisfactory.

3.2.2 Multi-Channel Communications in Target Tracking

In Publication IV the performance of networked estimation in contention-based multi-channel wireless networks was studied by focusing especially on the delay introduced by the MAC layer. In general, a problem in networked estimation is that multiple sensors transmit their estimates, or raw measured data, over a shared communication network. Due to the nature of contention-based communication systems, samples may be delayed excessively due to contention. Measurements contain random variations stemming from process and measurement noise while packet losses and limited sensing ranges cause randomness within the estimation process as well. Hence, we use the Extended Kalman Filter (EKF) [124] at the data fusion center to provide effective estimation and mitigate the impact of missing information on estimation performance. The exploitation of EKF requires Gaussian distributed noise values which occur in WSNs, e.g., in Time Delay of Arrival (TDOA)-based localization [75], [85], and in active and passive radar applications [123], [124].

The considered network scenario is a single-hop network where all nodes may interfere with each other. One or more GWs collect the measurement information from the sensor nodes and the received packets are then transmitted to the data fusion center using a high data rate technology such as IEEE 802.11 operating on a different frequency band. Furthermore, multiple channels can be used simultaneously when a single gateway node has multiple transceivers as well. In the simulation scenario, all sensors track the same target and measurements from different nodes are combined afterwards at the data fusion centre by using the EKF. Measurements are modeled in the simulations such that distances between the target and different sensors are calculated first, and then the measurement noise is added. The target tracking scenario is demonstrated in Figure 3.10 where the path of the target and the corresponding Kalman filter output, together with the positions of sensors, are shown.

Periodic and synchronized sampling was considered but if the target is outside of the sensing range the node does not send anything. Therefore, the application can be considered to be event-based. A sample is considered to be lost if it is not delivered within one sampling period, i.e., this

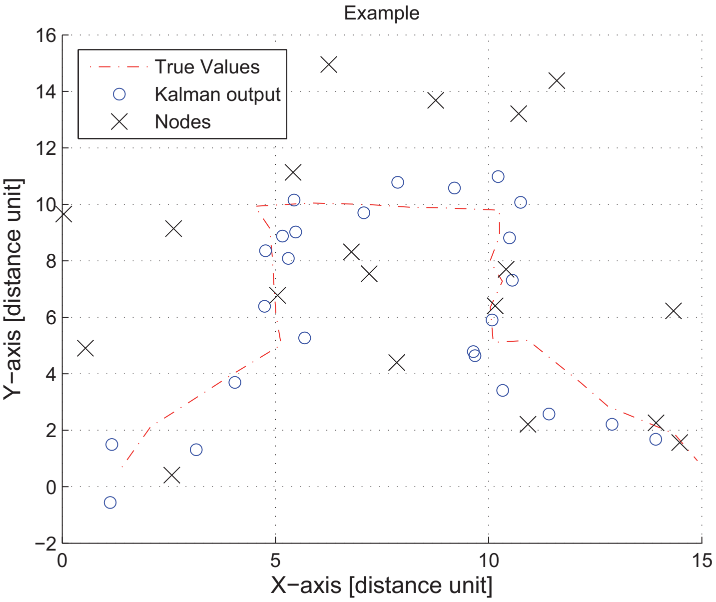


Figure 3.10. Target tracking scenario. ©2012 IEEE.

occurs when the delay of a packet is larger than the sampling period. To calculate the probability of packet loss, a Markov chain was constructed which models the operation of G-McMAC. The effect of packet losses on the Kalman filter updates is taken into account by using a selection matrix.

The number of measurements taken by each sensor depends on the length of the sampling period. The length of the sampling period is inversely proportional to the number of measurements since more samples can be taken if the sampling period is short. On the other hand, with small sampling periods the network becomes congested and packet losses occur more often. The main motivation behind Publication IV is to study the relationship between communication and estimation systems and show that the estimation performance can be improved by using multi-channel communications.

Due to the contention process and finite sampling period length, the probability of packet loss increases as the number of contending nodes is incremented. However, by exploiting multiple channels simultaneously the performance of the system can be improved. Figure 3.11 shows the effect of available channels on the performance of the Kalman filter. Curve $N = 1$ demonstrates the situation when only one data channel is available for use and is comparable to the performance of single-channel CSMA sys-

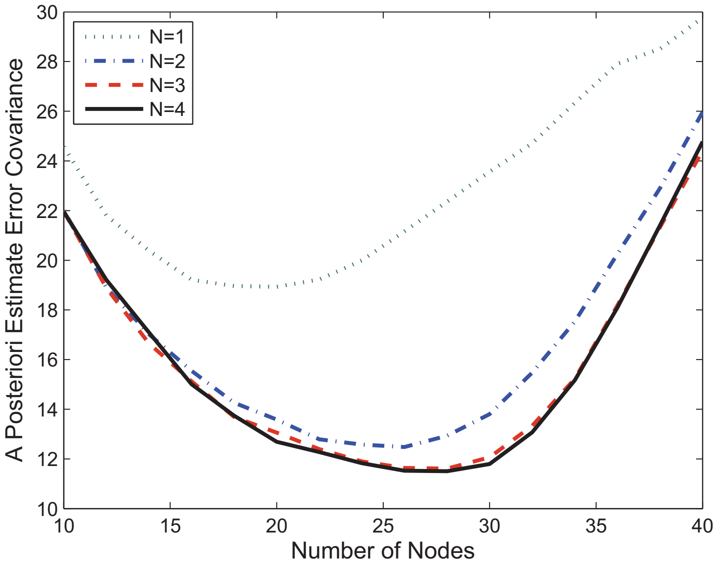


Figure 3.11. Estimation performance as a function of network size. ©2012 IEEE.

tems. As expected, by using additional channels it is possible to improve the estimation performance. Achievable gains increase as the number of nodes becomes larger. It can also be seen from the figure that the optimal number of nodes, which gives the best performance for some given parameters, is different for each number of channels. On the other hand, in this case the difference between $N = 3$ and $N = 4$ is negligible which demonstrates the fact that at some point the addition of an extra data channel does not offer significant benefit.

The optimal length of sampling periods was then investigated. Figure 3.12 illustrates the estimation performance as a function of sampling period length for different numbers of nodes. Network size, i.e., the number of nodes, is denoted by M. Results demonstrate the importance of parameter selection since the chosen network size determines the optimal sampling period length together with other parameters. From the figure it can be seen that the optimal length of sampling periods varies for different numbers of nodes; a larger number of nodes requires larger sampling periods.

Finally, the impact of sensing range on estimation performance was investigated in Publication IV as well. With smaller sensing ranges it was necessary to use a larger number of nodes to cover the entire area. However, in case of large sensing ranges it is possible to observe the area and

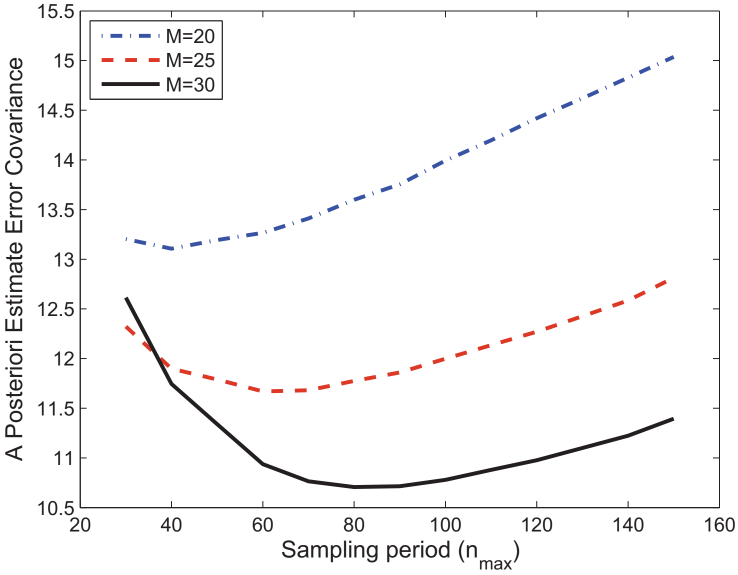


Figure 3.12. Estimation performance as a function of sampling period. ©2012 IEEE.

track the target reliably with less nodes. The derived theoretical results can be used to find the optimal communication and estimation parameters for different scenarios. This was demonstrated by analyzing an example scenario.

3.3 Time Synchronization in Multi-Channel Networks (Publications V & VI)

In Publication V a time synhcronization protocol is proposed that exploits multiple frequency bands simultaneously to minimize the convergence time of the synchronization process. In Publication VI this work is extended significantly by considering important theoretical issues, e.g., convergence time bounds for individual nodes and entire networks. Furthermore, the performance of the proposed protocol with respect to different critical operation parameters such as the number of available channels, network density, and transmission range of nodes is simulated and analyzed. The root node selection problem is also considered in Publication VI and a suitable solution for the problem is presented.

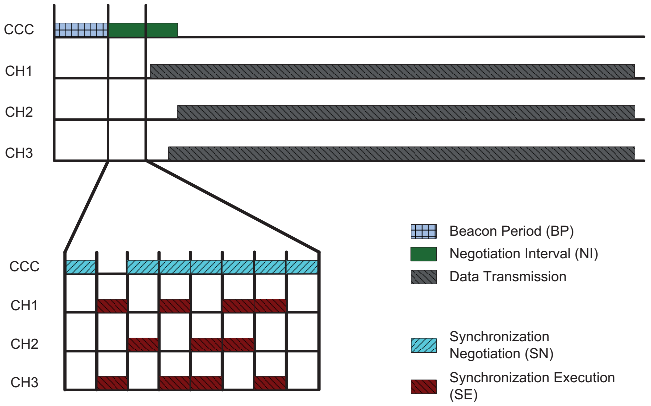


Figure 3.13. Demonstration of MCTS operations. ©2009 IEEE.

3.3.1 Proposed Time Synchronization Protocol

The Multi-Channel Time Synchronization (MCTS) protocol is a master-slave protocol where all slave nodes synchronize to a pre-selected root node. In small wireless sensor networks, the GW can act as a root node and provide a time reference for the entire network. However, in moderate sized WSNs the root node should be in the middle of the network to minimize both convergence time and synchronization errors. The root node selection problem for moderate sized networks is discussed in detail in Publication VI.

In general, a functioning MAC protocol is a prerequisite for the successful operation of time synchronization schemes; this is also the case with MCTS. To be more specific, MCTS requires a functioning multi-channel MAC that uses periodic beaconing. The synchronization protocol has three phases: Hierarchy Discovery (HD), Synchronization Negotiation (SN), and Synchronization Execution (SE). First, HD phases are used to create a synchronization hierarchy and keep the hierarchy up to date in order to cope with topology changes and node mobility. SN and SE are used for the actual synchronization process and these phases always follow a HD phase.

An example of operations for MCTS in a multi-channel network is illustrated in Figure 3.13. First, the selected root node sets one channel to be the CCC. The HD phase is carried out during the BP and the SN and SE phases are carried out during the Negotiation Interval (NI).

At the beginning of a HD phase, a selected root node broadcasts a Hierarchy Beacon (HB) message at the beginning of a BP which includes a root node's ID, synchronization level 1, and a list of available channels in addition to a send time stamp. All the nodes that receive this HB message set their synchronization level to 2 and broadcast a similar HB message with a new send time stamp. At this point the nodes at level 2 set the root node as their master and synchronize to it in a coarse manner by using the time stamps they received. This process goes on until every node in the network has found its level in the hierarchy and broadcasted a HB message.

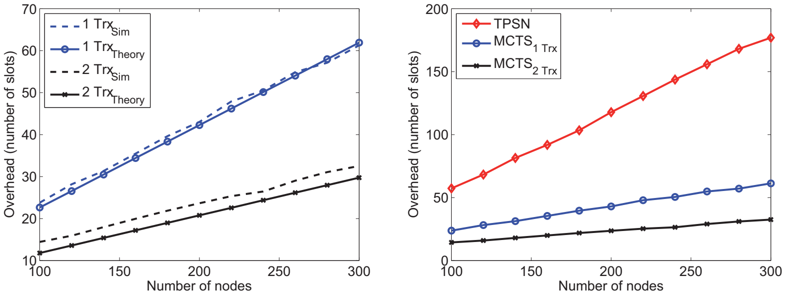
When the synchronization hierarchy has been created, MCTS proceeds to the NI. This begins with the root node announcing on the CCC that it is ready to start the synchronization process. All its slaves should contact it and negotiate a channel for synchronization, and after agreeing on the used synchronization channel, both the master and the slave tune to the synchronization channel and carry out the actual time synchronization. When a slave has been synchronized it announces on the CCC that it is ready to be a master for other nodes, if necessary. Then all its slaves contact it and negotiate for synchronization channels. Synchronization is then performed on the selected channel. The exact operations depend on the number of transceivers per node, the number of available channels, and network topology. In Publication VI a case study is presented to clarify the operations of MCTS.

The SE phase is initiated by a slave and it consists of two messages: Synchronization request (Sreq) and Synchronization response (Sres). MCTS exploits conventional two-way time synchronization for highest accuracy.

The slave first transmits a Sreq message to the master, that includes the slave and master IDs, and a send time stamp (T_1). The master should time stamp the incoming Sreq message with T_2. After receiving the packet, the master creates and transmits a Sres message which contains the master ID, slave ID, T_1, T_2, and the send time T_3. Finally, the slave time stamps the incoming Sres with T_4 and after collecting all the time stamps, the slave node can be synchronized to the master and the propagation delay (d) and clock offset (Θ) can be calculated as follows

$$d = \frac{(T_2 - T_1) + (T_4 - T_3)}{2}, \tag{3.17}$$

$$\Theta = \frac{(T_2 - T_1) - (T_4 - T_3)}{2}. \tag{3.18}$$



(a) Theoretical and simulated results. **(b)** Performance comparison.

Figure 3.14. MCTS: Convergence time as a function of network size.

3.3.2 Network Convergence Time

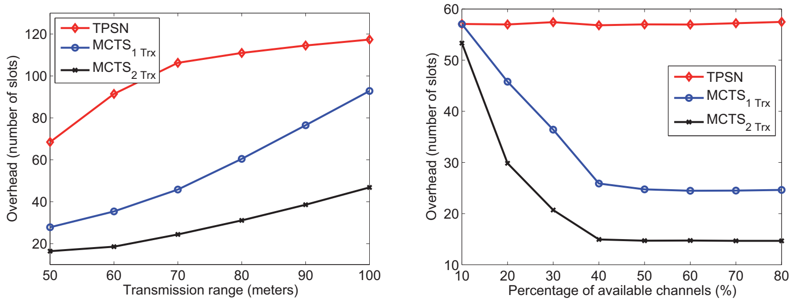
The convergence time of the synchronization process in multi-channel systems depends on various design parameters. The number of transceivers per node determines how many slave nodes one master can synchronize simultaneously while the network topology determines the number of levels in the synchronization hierarchy. Another critical parameter is the maximum number of slave nodes (M_{slaves}) that a master node may have. This is closely related to the network density (nodes/area).

In Publication VI an approximation is given for evaluating the convergence time of MCTS in terms of slots. The expected number of hierarchy levels, denoted by $\tilde{H}$, is calculated first by using the distance from the centre of the network to the edge as well as transmission range. Then, the maximum number of slave nodes is estimated. As a result, if the number of available channels is large enough, i.e., $N \gg M_{slaves}$, the convergence time of a typical MCTS synchronization process can be approximated as follows

$$O_{MCTS} = \tilde{H} + \frac{M_{slaves}}{X} \cdot (\tilde{H} - 1), \tag{3.19}$$

where X is the number of transceivers each node has.

Figure 3.14a illustrates the theoretical and simulated results. As the figure demonstrates, the theoretical results match well with the simulations for moderate network density. Even though in this theoretical analysis it is assumed that the network topology is spread out widely, i.e., slave nodes of each master are not in the transmission range of each other, the theoretical and simulated results match well. Therefore, these theoretical results can be used to estimate performance.



(a) Effect of transmission range. **(b)** Effect of the number of channels.

Figure 3.15. Simulation results: MCTS versus TPSN.

A performance comparison between MCTS and TPSN was carried out using Matlab simulations. In the first simulation, 16 channels were available for all WSN nodes, except the channels that were occupied by a Wireless Local Area Network (WLAN) transmitter (4 channels), and the effect of network size on the performance of MCTS and TPSN was studied. Convergence times as a function of network size are shown in Figure 3.14b. The convergence time of TPSN grows linearly when the number of nodes in the network is increased. MCTS performs similarly as a function of network size, however, since neighboring master nodes can use different channels for synchronization execution, the slope of the MCTS curve is significantly smaller. In general, the benefit gained using MCTS grows as the size of the network increases. The performance is quite stable for MCTS as the network size grows whereas the convergence time of TPSN is heavily affected by the number of nodes.

Convergence times as a function of the wireless sensors' transmission range are presented in Figure 3.15a for MCTS and TPSN. The transmission range of wireless sensors has a large effect on the performance of TPSN since all masters have to synchronize on the same channel and are able to synchronize only one slave at a time. The results imply that MCTS performs significantly better than TPSN for the case of small transmission ranges but the difference shrinks when transmission range is increased. The reason for this is that in case of large transmission ranges each master node has many slaves and consequently multiple channels cannot be fully exploited due to the small number of transceivers. The resulting effect is that as the transmission range grows the achieved gain from using two transceivers increases.

Finally, the effect of the number of available channels on the performance of MCTS was simulated as well. Convergence times as a function of available channels are depicted in Figure 3.15b. Naturally, the number of available channels does not have any effect on the convergence time of TPSN. When the number of available channels is low, the number of transceivers has a negligible influence on the performance of MCTS. This is due to the fact that the probability that a master and its slaves would share many available channels is extremely low. However, when the number of available channels is increased, the performance of MCTS quickly improves. In this scenario the performance of MCTS saturates when 40 % of the channels are available. Therefore, only a small number of available channels is sufficient for MCTS to achieve optimal performance. In summary, these results indicate that by using MCTS significant gains can be achieved when compared to conventional single-channel time synchronization schemes.

3.4 Timing & Sensing in Cognitive Radio Networks (Publications VII & VIII)

Publications VII and VIII consider energy detection of primary users signals' under timing inaccuracy in CR networks. In Publication VII a novel mathematical model for calculating the impact of interfering nodes on energy detection is presented together with closed-form solutions for the probabilities of detection and false alarm. Whereas, in Publication VIII a novel interference suppression algorithm to mitigate the impact of other transmissions of secondary users on sensing was designed and its performance was analyzed using simulations.

3.4.1 Interference due to Timing Errors

Figure 3.16 illustrates the general effect of timing errors on CR frames and sensing. In the figure, User 1 has the correct time reference and since the clock of User 2 is ahead, User 2 starts transmitting too early and as a result, creates interference at the end of the sensing slot. Respectively, User 3 is unable to stop transmitting by the start of User 1's reference sensing slot since its clock is behind the reference clock. The amount of timing error determines how much interference is caused and varies for nodes with different timing errors.

The received signal $r(n)$ can be presented with the following hypothe-

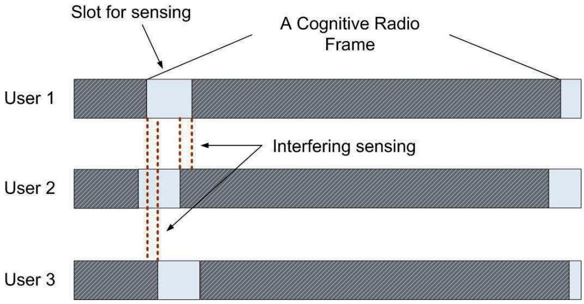


Figure 3.16. Effect of timing errors on sensing. ©2010 IEEE.

ses. All the signals are complex and the noise signal $w(n)$ is modeled as AWGN. Hypothesis H_0 denotes the case in which the primary user is not present and H_1 represents the case in which the primary user is present, i.e.,

$$r(n) = \begin{cases} w(n) + z(n) & : \quad H_0 \\ s(n) + w(n) + z(n) & : \quad H_1, \end{cases}$$

where $s(n)$ denotes the received signal from the primary user and $z(n)$ the received interference from other secondary users.

Decision making is based on comparing the decision metric L with the threshold λ_L. The decision metric is given by

$$L = \frac{1}{\tilde{N}} \sum_{n=1}^{\tilde{N}} |r(n)^2|, \tag{3.20}$$

where $\tilde{N}$ is the number of samples. For example, a false alarm occurs if the decision metric is larger than the threshold even though there is no transmission from a primary user and the probability of a false alarm can be defined as

$$P_f = Pr(L > \lambda_L | H_0), \tag{3.21}$$

In practice, system design is generally based on the false alarm probability if there is no knowledge about primary users' signals. This means that the detection threshold is calculated by fixing the target false alarm probability. In case of energy detection, the probability of false alarm is [36]

$$P_f = \frac{\Gamma(\tilde{N}, \frac{\lambda_L}{2\sigma_w^2})}{\Gamma(\tilde{N})}, \tag{3.22}$$

where σ_w^2 is the variance of noise, $\Gamma(\alpha)$ the gamma function and $\Gamma(\alpha, \beta)$ the incomplete gamma function.

The length of the sensing slot is denoted by τ_s while the total length of one cycle (sensing plus data transmissions) is denoted by T_c. Now, if

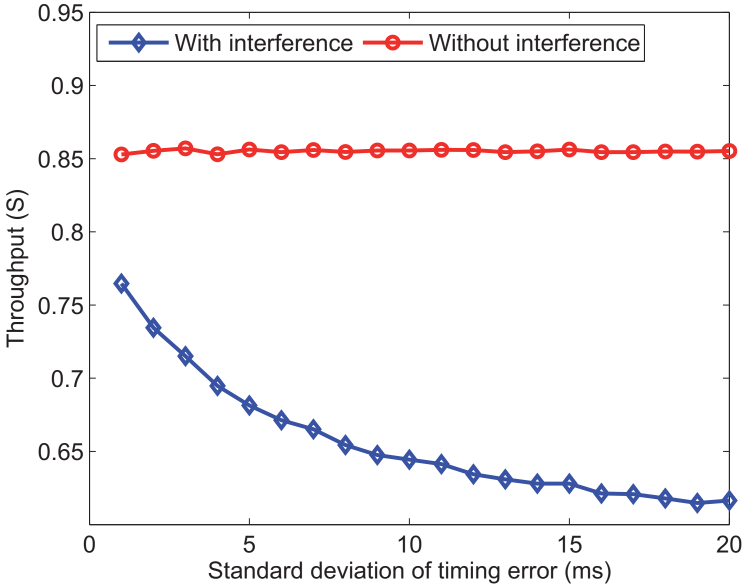


Figure 3.17. Impact of intra-network interference on throughput. ©2010 IEEE.

the primary user is not present, the maximum achievable throughput of secondary networks can be presented as

$$S = \frac{T_c - \tau_s}{T_c}(1 - P_f)C, \tag{3.23}$$

where C is the capacity of the secondary network. From Eq. (3.23) it can be seen that an increase of false alarm probabilities decreases the throughput of secondary networks.

To show an example of the interference caused by other CR users due to timing misalignments, a scenario was simulated in which 21 CR users where randomly positioned on a rectangular area of 1 km^2 while $\tau_s =$ 20ms, $P_f = 0.1$, $\tau_s = 0.05 \cdot T_c$, and $C = 1$. In this simulation the timing error of each user was randomly selected according to the distributions of timing errors and the target probability of false alarm was set to 10 $\%$. Figure 3.17 illustrates the results and shows the impact of timing misalignments on the throughput of secondary networks.

Since the probability of false alarm increases as the standard deviation of timing errors grows, the throughput of secondary networks degrades as a function of timing errors. The reason for this is that CR users stop data transmissions unnecessarily due to intra-network interference even though a primary user is not present. However, without intra-network interference the system performance is naturally stable.

3.4.2 Detection in the Presence of Timing Errors

In Publication VII a novel mathematical model is presented which enhances the classical energy detection models by taking into account the impact of other CR users that interfere with sensing due to timing errors. Each user transmits with a certain probability and exhibits a random timing error. The interference experienced by each node is therefore different for each sensing interval even though the experienced interference will be the same for all nodes in the long run since it is assumed that the mean of the timing error is zero.

During a sensing interval, a node experiences interference due to the transmissions of some neighbors. However, it is clear that all its neighbors cannot be transmitting simultaneously on the same frequency channel. A transmission matrix can consequently be derived which contains all possible link combinations, i.e., transmitter-receiver pairs. Furthermore, a matrix that includes the signal's properties experienced by this particular user for each transmission combination can be deduced as well. By using these matrices the probabilites of false alarm and detection under intra-network interference due to timing errors can be derived.

The correctness of the theoretical model is verified through Matlab simulations. Variable $\sigma_z(n)$ signifies the standard deviation of interference of the nth sample and σ_s denotes the standard deviation of the primary user's signal. The model is verified by simulating the following interference cases:

- Case 1: $\sigma_z(n) = [0, 0, 0, 0, \cdots, 0, 0, 0, 0]$
- Case 2: $\sigma_z(n) = [2\sigma_s, \sigma_s, 0, \cdots, 0, \sigma_s, 2\sigma_s]$
- Case 3: $\sigma_z(n) = [4\sigma_s, 3\sigma_s, 2\sigma_s, \sigma_s, 0, \cdots, 0]$
- Case 4: $\sigma_z(n) = [3\sigma_s, 2\sigma_s, \sigma_s, 0, \cdots, 0, \sigma_s, 2\sigma_s, 3\sigma_s]$

In Case 1, the probability of correct detection is simulated without any interference caused by other secondary users, which is the theoretical upper bound for performance. Case 2 represents a situation where the timing error is 0 and the received interference is symmetric on both ends of the sensing slot. Moreover, Case 3 demonstrates the situation for nodes

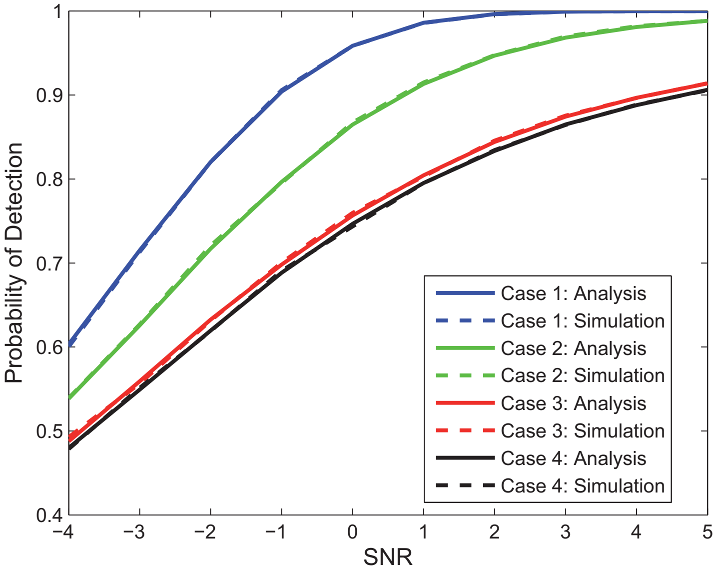


Figure 3.18. Theoretical and simulated results for example cases. ©2010 IEEE.

with a maximum timing error such that the interference affects only the other end of the sensing slot. Case 4 illustrates the impact of increased interference when compared to Case 2.

Figure 3.18 illustrates both analytical and simulation results as a function of SNR which is specified as $\frac{\sigma_s}{\sigma_w}$. As can be seen from the figure, the derived representation models the behavior of energy detection correctly for all cases. These results imply that the effect of interference is significant since the probability of correct detection is much higher for the first case than for the other cases. It can thus be inferred that intra-network interference should not be neglected when designing secondary systems.

3.4.3 Interference Suppression under Timing Inaccuracy

As discussed earlier, the effect of intra-network interference caused by the timing errors of secondary users can degrade the performance of cognitive radio networks. The problem can be naturally avoided by implementing accurate time synchronization. However, in some cases it may be impossible to achieve precise network-wide time synchronization and hence, in Publication VIII, a novel interference suppression scheme is presented which can be used for such situations.

The proposed interference suppression algorithm, called Interference

Suppression for Cognitive Radios (ISCR), is designed to mitigate the impact of other secondary users' transmissions on sensing in case of timing errors. The foundation of the proposed algorithm is that in order to maximize the performance of detection, it is desirable to give more weight to the samples that experience the least interference, and as a consequence, are more reliable. The objective is to minimize the difference between the received signal without interference and the weighted signal estimate.

The effect of randomness should be minimized in order to achieve maximum detection performance. To attain this, the sensing window $\tilde{N}$ is divided into multiple blocks B such that $\tilde{N}/B \in \mathbb{N}_1$ and the weight is estimated for each subset individually. The standard deviation of the received signals is calculated for each of the signal blocks b, denoted by σ_b, and these values are used to estimate the corresponding weights ω_b. Each sample is associated with the estimated weight of its signal block. The number of samples in each block is denoted by $N_b = \tilde{N}/B$. Therefore, the weighted decision metric becomes

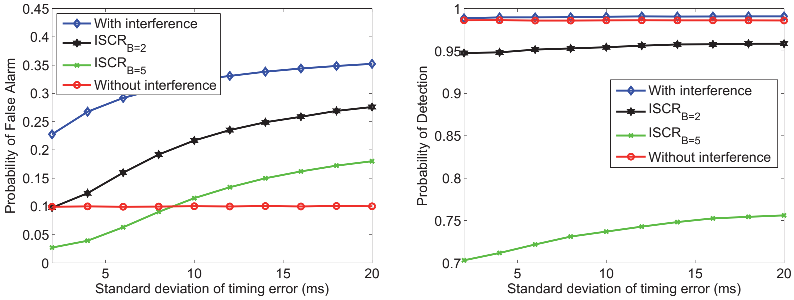
$$\tilde{L}_w = \frac{1}{\tilde{N}} \sum_{i=1}^{B} \sum_{j=1}^{N_b} \omega_i \cdot |r(i,j)|^2, \tag{3.24}$$

where $r(i,j)$ denotes the j^{th} sample in a signal block i. An optimization problem for assigning the weights is formed and solved in Publication VIII. As a result, the optimal value of weight ω_b is

$$\omega_b^* = \frac{B}{\sigma_b^2 \sum_{i=1}^{B} \frac{1}{\sigma_i^2}} = B \frac{\Pi_{k=1,k\neq m}^{B} \sigma_k^2}{\sum_{i=1}^{B} \left(\Pi_{j=1,j\neq i}^{B} \sigma_j^2 \right)}. \tag{3.25}$$

Detection performance was first studied from the secondary users' perspective. Figure 3.19a shows the achievable benefit in terms of the false alarm probability in the presence of intra-network interference. It can be observed that for the case of small timing errors, ISCR with two blocks ($B = 2$) performs extremely well and achieves a level of performance that is identical to the one without interference; this is naturally the upper bound for performance. However, when timing errors grow, the performance of ISCR deteriorates slightly. The reason behind this behavior is that ISCR cannot improve detection performance as much if timing errors are remarkably large and the received interference becomes close to a constant level over all the samples on average. Since ISCR decreases false alarm probabilities it provides higher throughputs for secondary networks.

Figure 3.19b presents the simulation results for the probability of detection. ISCR definitely has some effect on the probability of detection since



(a) Probability of false alarm.

(b) Probability of detection.

Figure 3.19. Performance of ISCR as a function of timing errors. ©2010 IEEE.

the received interference powers are scaled down and therefore, in general, the probability of detection is reduced. This is due to the fact that complete information about the interfering signals is not available and estimates are used for weighting the samples. The results imply that it is difficult to achieve very high probability of detection, such as $P_d = 0.99$, with ISCR even though moderate detection probability, $P_d = 0.95$, can be achieved. It should be noted that the probability of detection can be significantly improved by connecting the secondary network to a data base which provides information about the spectrum availability. Hence, ISCR should be feasible in its present form. Moreover, in Publication VIII energy detection was considered which achieves the worst sensing accuracy. The performance of ISCR can be improved by applying more advanced sensing methods as well.

Figures 3.19a and 3.19b represent two sides of the same coin and by comparing the figures it can be seen that there is a trade-off to consider. If it is desirable to maximize the throughput of the secondary users, primary users have to pay a small price. Consequently, if maximization of the probability of detection is the goal, ISCR should not be used. Moreover, it is clear that under the current simulation setup the only feasible number of blocks is two to ensure sufficient primary user protection. This has been verified in different scenarios and all results indicate similar behavior. Nonetheless, from these simulation results it is inferred that the impact of ISCR on the probability of detection is fairly small if the block size is two and hence, ISCR is applicable from the primary users' perspective as well. In other words, ISCR with two blocks achieves a balance between maximizing the throughput of CR users while providing sufficient protection for primary users.

4. Conclusions & Discussion

In wireless sensor networks (WSNs) sensors measure the environment in a distributed manner. The gathered data is then transmitted using a wireless communication network to one or more gateways which collect and potentially process the information. WSNs enable numerous novel applications that can be used to address various problems within the fields of industry, environment, society, and military. Wired sensor networks have already been used in many applications, however, wireless communication systems offer flexible positioning and lower installation costs when compared to wired systems. These issues make WSNs a potential communication solution for many applications which have used wired networks previously. Furthermore, the physical constraints of cables limit the application scenarios of wired sensor networks. Therefore, the exploitation of wireless systems has the potential to enhance the application domain of sensor networks.

Due to the uncertain transmission medium, many problems arise that do not exist in wired networks since packet losses and varying delays characterize the performance of WSNs. Design challenges of resource constrained WSNs cover reliability, robustness, interference and scalability issues. Multi-channel communications provide a way to effectively exploit available spectrum and offer high performance and trustworthy delivery of packets. Moreover, by using multiple channels it is also possible to enhance the performance of time synchronization protocols. The main focus of this thesis was on the exploitation of multi-channel communications in WSNs by concentrating on the Media Access Control (MAC) layer and time synchronization.

In this thesis, a novel multi-channel MAC protocol, called Generic Multichannel MAC (G-McMAC), designed particularly for industrial WSN applications, was presented. The performance of multi-channel MAC protocols in ad hoc networks was studied with respect to two important Quality of Service (QoS) parameters: delay and throughput. These parameters were analyzed in terms of critical system paramaters such as the number of available channels, arrival rate, and packet sizes. The presented results indicate that G-McMAC outperforms other existing protocols with respect to delay while also providing the highest throughput in many cases. However, the low stability point of G-McMAC may be a problem for some applications and therefore it would be important to study how to improve this part of the protocol design. The protocol has been implemented on ns-2 and simulation results from an example industrial application scenario confirmed that GMcMAC is suitable for industrial wireless sensor applications. Nevertheless, since ns-2 has some limitations, it would be beneficial to implement G-McMAC on real sensor nodes. For example, the ns-2 simulator does not model the operation of nodes accurately leading to approximate modeling of processing times, channel switching penalty, etc.

Poisson distributed packet arrivals were considered in the analysis. This distribution has been widely used to model the packet arrival process in communication systems. The applicability of the Poisson arrival process for modeling traffic has been discussed in [52] as well. In short, Poisson distributed packet arrival is not suitable for modeling internet traffic, however, it can be used to model user-initiated sessions like telephone calls, file and mail transfers, etc. In the case of wireless automation, Poisson distributed traffic typically arises if the application in question is event-driven. Such arrival processes occur, e.g., when using the send-on-delta method when the process is driven by Gaussian noise. Moreover, if the network consists of many unsynchronized sensor nodes, or a Poisson sampling process is employed, the packet arrival process follows the Poisson distribution as well.

In this thesis the Poisson arrival process was used in Publication II and Publication III. In Publication II it was used to compare the performance of the multi-channel MAC protocols in case of intermittent packet generation and the Poisson arrival process is suitable for that. Furthermore, in Publication III multiple, independent control loops were considered. In this case the events were not correlated and the Poisson arrival process can be used to model packet arrivals in such situations as well. On the other hand, in Publication IV a target tracking scenario was considered where the physical events were highly correlated and hence, the Poisson arrival process was not used in the publication.

The utilized MAC protocol has a significant impact on applications since it is the main source of delay uncertainty, especially in distributed wireless systems. Two different applications were considered, wireless automation and networked estimation, and G-McMAC was used in both cases since minimization of delay and delay variance is crucial for these applications. Consequently, the analysis focused on delay since it is of significant importance to understand the delay properties of the used communication protocols which end up directly affecting the design and operation of networked control systems.

In the case of wireless automation, the relationship between the critical communication and control parameters was evaluated by using the First Order Lag plus Integrator plus Delay (FOLIPD) process model together with Proportional-Integral-Derivative (PID), and Internal Model Control (IMC) controllers. Results show that it is important to study both parts of the wireless automation system together in order to design a feasible and working system. Additionally, these results demonstrate the trade-off between the chosen communication and control parameters as well.

A target tracking application was studied as an example of networked estimation applications. By using the derived theoretical results the combined effect of the chosen communication and estimation parameters on the performance of target tracking was investigated. Additionally, a selection of communication and estimation parameters for achieving optimal performance was studied by analyzing an example scenario. It was shown that optimal performance can be achieved by choosing parameters properly. Furthermore, the derived theoretical results can be utilized to find optimal communication and estimation parameters in different scenarios. In this theoretical work it was assumed that packet losses are i.i.d. Bernoulli distributed which is naturally not the case in practice since the probability of packet loss varies for different transmission windows. However, this assumption should not affect the results significantly since the impact of this assumption is averaged over the long run.

In general, time synchronization is essential for many WSN applications and accurate timing also enables intelligent and efficient communications between sensor nodes. Multi-channel communications can be used to speed up the synchronization process and thereby reduce convergence times. A novel protocol for time synchronization of multi-channel wireless sensor networks, the Multi-Channel Time Synchronization (MCTS) protocol, was introduced. The unique features of the proposed MCTS include achieving network-wide synchronization using a fully distributed protocol and exploiting multiple channels to reduce convergence time. MCTS exploits multiple transceivers as well, when available.

The convergence time of the protocol was studied theoretically and the performance of MCTS was evaluated by simulations. It was shown that the simulation results match the theoretical results well. Furthermore, it was observed that MCTS outperforms Timing-sync Protocol for Sensor Networks (TPSN) clearly and functions well even if only a small number of channels is available. Simulations were performed using Matlab and therefore the results are not directly comparable with real-world scenarios. However, these simulation results can be used to evaluate the performance of the protocols when compared to each other. In summary, MCTS outperforms other existing solutions such as TPSN in multichannel WSNs and can be considered as a promising candidate for time synchronization in future multi-channel WSNs.

Since MCTS can be used in any multi-channel network it is applicable to Cognitive Radio (CR) networks as well. With CR as the enabling technology, multiple available channels can be identified by the sensor nodes in a Cognitive Radio Sensor Network (CRSN). In fact, CR networks offer additional motivation for time synchronization since generally it is assumed that all secondary users are quiet and sense channels at the same time to detect the presence of a primary user.

The effects of timing errors on energy-based incumbent detection in decentralized CR networks were therefore studied as well. A novel detection model that takes into account the interference caused by other CR users was proposed and closed-form solutions for correct detection and false alarm probabilities were derived. It was demonstrated that the interference caused by other secondary users is a significant problem, and since timing errors cause degradation of sensing performance in distributed CR networks, as the results show, accurate time synchronization is important. Nevertheless, precise time synchronization may not always be possible to achieve which gave motivation for designing a novel interference suppression method for such cases.

Interference Suppression for Cognitive Radios (ISCR) was introduced for the purpose of suppressing the effect of intra-network interference in decentralized cognitive radio networks under timing errors. The algorithm was designed to maximize the throughput of decentralized secondary systems under timing errors while sufficiently protecting primary users' transmissions. ISCR is simple, efficient, and can be carried out in real time since it utilizes straightforward calculations. Furthermore, ISCR can be incorporated with all energy detectors which makes it feasible for various CR networks. Simulation results verified that ISCR improves the perfomance of distributed CR networks significantly in practice by minimizing the probability of false alarm under timing errors. These simulation results were performed using a certain simulation scenario. If a different channel model or network scenario were used, the results would be different. However, in general, the behavior will be similar regardless of the used models and scenarios since only the received signal powers are scaled depending on the parameters.

Naturally, an important next step is to implement the protocol on real nodes to gain knowledge about its performance in practice. Furthermore, the performance of G-McMAC could be improved by fine-tuning the operations of the protocol. It seems that the capacity of the Common Control Channel (CCC) causes problems when significant amounts of traffic is fed into the network. By dynamically changing the bandwidth of the CCC it could be possible to avoid such problems and improve the performance of G-McMAC. Furthermore, even though energy conservation is often of utmost importance in WSNs it has not been studied in the case of G-McMAC. Since G-McMAC is essentially a contention-based protocol, it is expected that energy saving schemes designed for single-channel contention-based systems should be suitable for G-McMAC as well. However, in WSNs it could be beneficial to schedule sleeping times based on the experienced traffic and take into account the traffic patterns of different applications [11]. In multi-channel communication systems, traffic patterns are different than in single-channel networks due to the possibility of simultaneous transmissions in the same area. Therefore, the use of sleeping methods together with G-McMAC would be a good topic for future research as well.

The impact of G-McMAC on two different applications was studied but since the application domain of WSNs is very large, it should be possible to find many other potential applications in which G-McMAC could bring significant benefits. In general, many event-based applications could profit from G-McMAC. For instance, how G-McMAC affects the performance of event-based PID controllers would be another interesting topic for future research.

Although MCTS seems to perform well compared with TPSN in theory, the achievable gains may not be significant in practice. Due to this MCTS should be implemented on real hardware to be able to see whether it is important to use multi-channel communications for time synchronization in practical WSN implementations or not. MCTS should be implemented together with a suitable multi-channel MAC protocol, such as G-McMAC. It would then be possible to comprehensively study multi-channel communications in real-world WSN scenarios.

Furthermore, only the impact of timing errors on CR networks in case of energy detection was studied but it would be equally important to extend this study by considering other sensing methods as well. Intuitively, the impact of timing errors may not be as large in case of matched-filtering, for example. Nevertheless, a detailed investigation of different sensing methods would be required in order to draw valid conclusions. Existing interference suppression methods should be reviewed by taking into account different sensing methods, and based on this, new schemes may be required if existing ones do not perform sufficiently well.

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