Cognitive Multi-Radio as Enabler for Deterministic Dynamic Spectrum Access

Wireless Innovation Forum European Conference on Communications Technologies and Software Defined Radio (WInnComm-Europe)

Matej Kloc, Norman Franchi, Markus Gardill, Robert Weigel

Erlangen, 8th October 2015

Institute for Electronics Engineering
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FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG
TECHNISCHE FAKULTÄT

Agenda

1. Motivation
2. Approach – Cognitive Multi-Radio
3. Measurements
4. Evaluation
5. Summary

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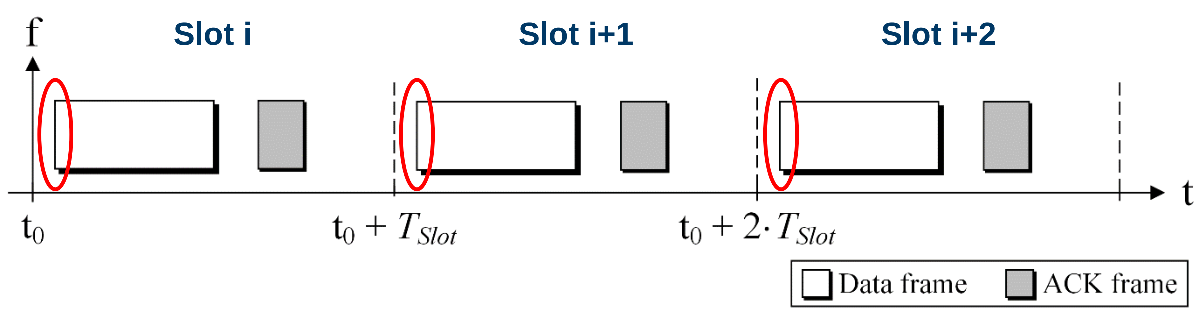
1. Motivation

Industrial Wireless Communications (IWC)

- **Applications**
  - Process control and automation
  - Monitoring
  - Motion control (e.g. in robotics)

- **Short-Real-Time Requirements**
  - High reliability / determinism
  - Low latency
  - Low cycle times (<5 ms) [1,2]

- **Deterministic Dynamic Spectrum Access (D-DSA)**
  - TDMA[1] / time-slotted communication scheme for real-time IWC



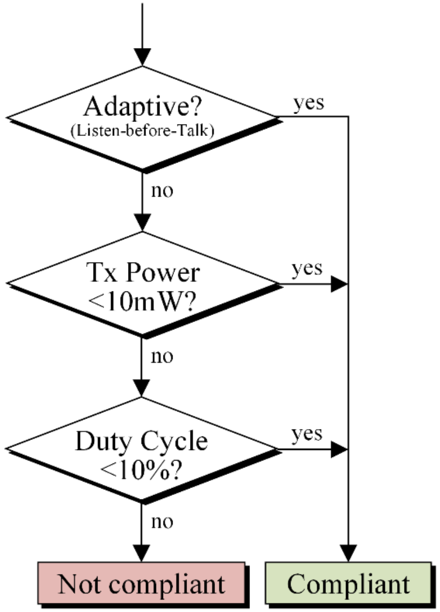
  - DSA in every time slot required for deterministic transmission of time-critical process data

[1]) TDMA = Time-Division Multiple Access

1. Motivation

Current Situation

- **Problems / Limitations of IWC Systems**
  - No exclusive frequency band for IWC
  - Operation in licence-free frequency bands [3]
    - Primary in 2.4 GHz ISM[1] band (2.40-2.4835 GHz)
    - Highly crowded → coexistence problems
    - Repeated frequency (re-)planning for reliable operation
  - Limitations on spectrum access by regulations
    - ETSI EN 300 328 V1.9.1 [4]
    - Listen-before-Talk (LBT) mechanism for broadband and non-FHSS[2] systems required
    - Related works [5] are not considering the updated spectrum regulations
  - Current IWC technologies do <u>not</u> provide short-real-time capability
    - e.g. WirelessHART [6] → (fixed) time slot duration of 10 ms

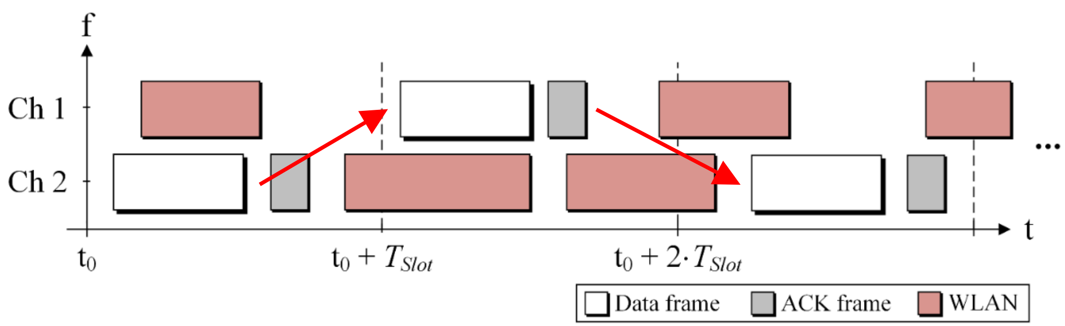


1) ISM = Industrial, Scientific and Medical
2) FHSS = Frequency Hopping Spread Spectrum

1. Motivation

Short-Real-Time IWC System

- **Solution**
  - Cognitive Radio (CR) technology for IWC in ISM frequency bands [7-9]
    - Observation of spectrum and adaptation of transmission parameters
    - Efficient utilization of (limited) spectrum resources
  - Operation on multiple channels as key enabler for broadband D-DSA under short-real-time requirements with low cycle times (<5 ms) and in presence of various wireless technologies (e.g. WLAN[1] devices)



  - Challenge → detection of unoccupied channel & switching during a time slot

1) WLAN = Wireless Local Area Network

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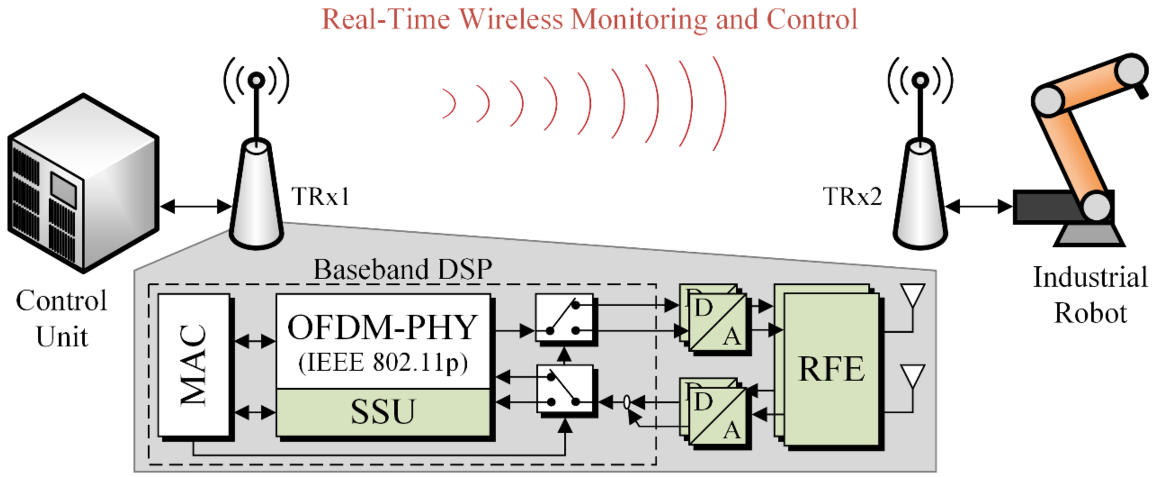
2. Approach – Cognitive Multi-Radio

Transceiver Concept for Short-Real-Time IWC

- **Architecture**



- Multiple Radio Front Ends (RFEs)
- Robust Physical Layer (PHY) based on Standard IEEE 802.11p
- Spectrum Sensing Unit (SSU)

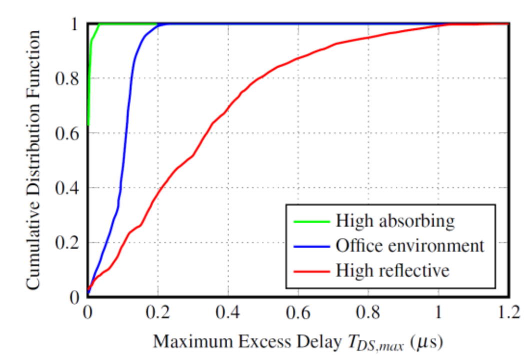
- Parallel observation of multiple channels with SSU
- Rapid channel selection / switching during a time slot (e.g. $T_{Slot} = 1\ \mathrm{ms}$)
- Improvement of D-DSA in ISM band

2. Approach – Cognitive Multi-Radio

Robust Physical Layer (PHY)

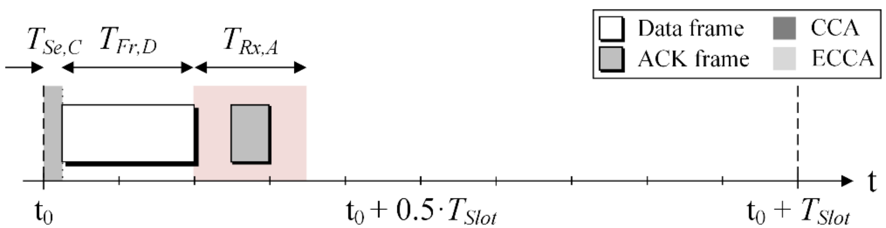
- **Standard IEEE 802.11p PHY for IWC** [10]
  - Primary intended for Car2Car / Car2X communications
  - Orthogonal Frequency-Division Multiplexing (OFDM)
    - Multi-carrier (broadband) modulation scheme
- **Why?**
  - High robustness against multi-path propagation
    - Highly reflective industrial environments (e.g. manufacturing hall)
  - Well dimensioned Guard Interval (GI)
    - $T_{GI,802.11p} = 1.6\ \mu\mathrm{s} > T_{DS,max} = 1.2\ \mu\mathrm{s}$
  - High adaptability
  - Higher achievable data rates
    - >12x higher than e.g. WirelessHART (IEEE 802.15.4)

Maximum Excess Delay Evaluation [11]

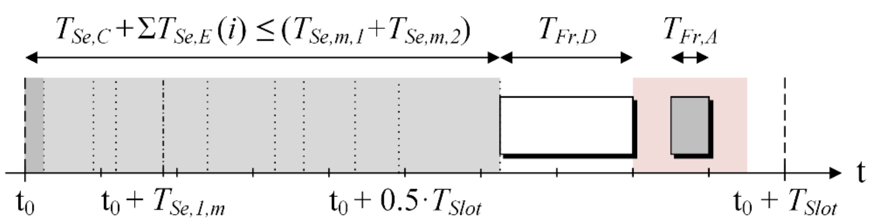


2. Approach – Cognitive Multi-Radio

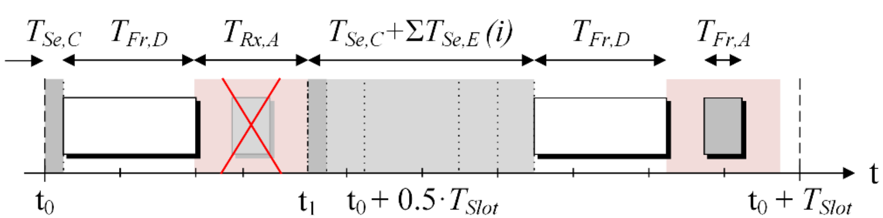
Spectrum Access Scheme [12]



a)



b)



c)

- Time-slotted communication scheme incl. Acknowledgement (ACK)
- Implementation of LBT mechanism
- Clear Channel Assessment (CCA) check before every transmission
  → $T_{Se,C} = 18\ \mu s$
- Extended CCA (ECCA)
  → $18\ \mu s \leq T_{Se,E} \leq 160\ \mu s$
- Optional retransmission during a time slot when data or ACK frame drops
- Compliance to ETSI EN 300 328 V1.9.1

2. Approach – Cognitive Multi-Radio

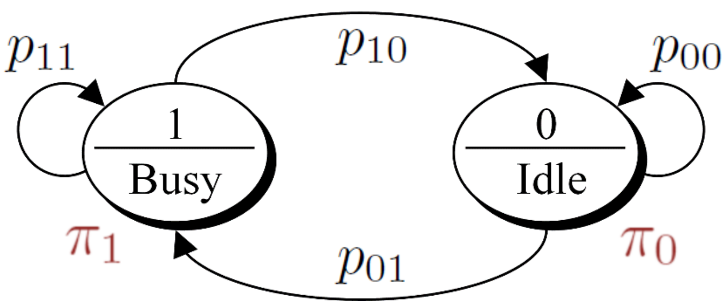
Channel Sensing & Modelling

- **Energy Detection**

$$Y_n(k) = \frac{1}{N_{Se}} \sum_{m=k}^{k+N_{Se}} |r_n(m)|^2 \underset{H_0}{\overset{H_1}{\gtrless}} \lambda_{th}$$ [13]

λ_{th}: Energy threshold
r_n: Received complex samples on n^th channel
N_{Se}: Number of sensing samples

- **Markov Model**
  - Modelling of traffic in ISM band as a time-discrete Markov chain [14]
  - Multi-channel sensing information used for learning the Markov model



π_i: Initial probability
p_{ij}: Transition probability

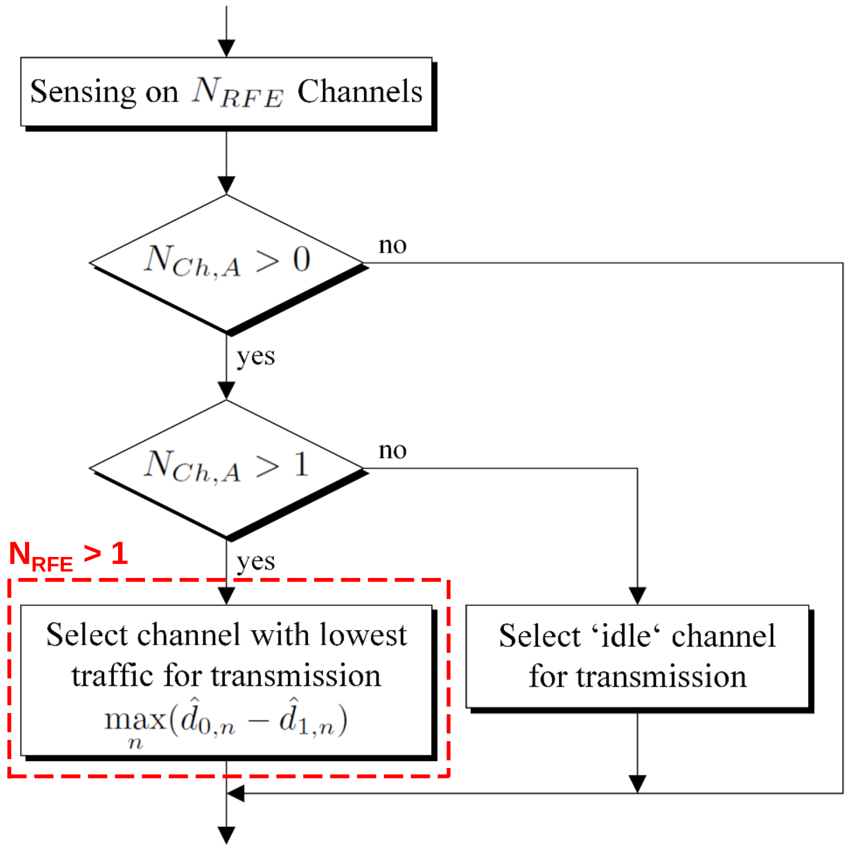
Channel with lowest traffic / occupancy

$$\max_n(\hat{d}_{0,n} - \hat{d}_{1,n}) = \max_n\left(\frac{\pi_0}{1-p_{00}} - \frac{\pi_1}{1-p_{11}}\right)$$ [14]

with $n \in \{1, \ldots, N_{RFE}\}$

2. Approach – Cognitive Multi-Radio

Channel Selection Strategy



Number of available (‘idle‘) channels

$$0 \leq N_{Ch,A} \leq N_{RFE}$$

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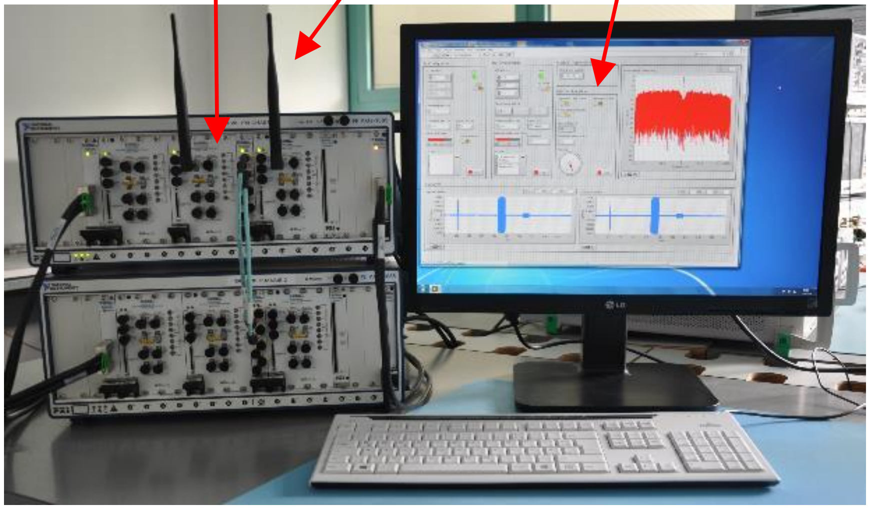
3. Measurements

For Coexistence Analysis in the 2.4 GHz ISM Frequency Band

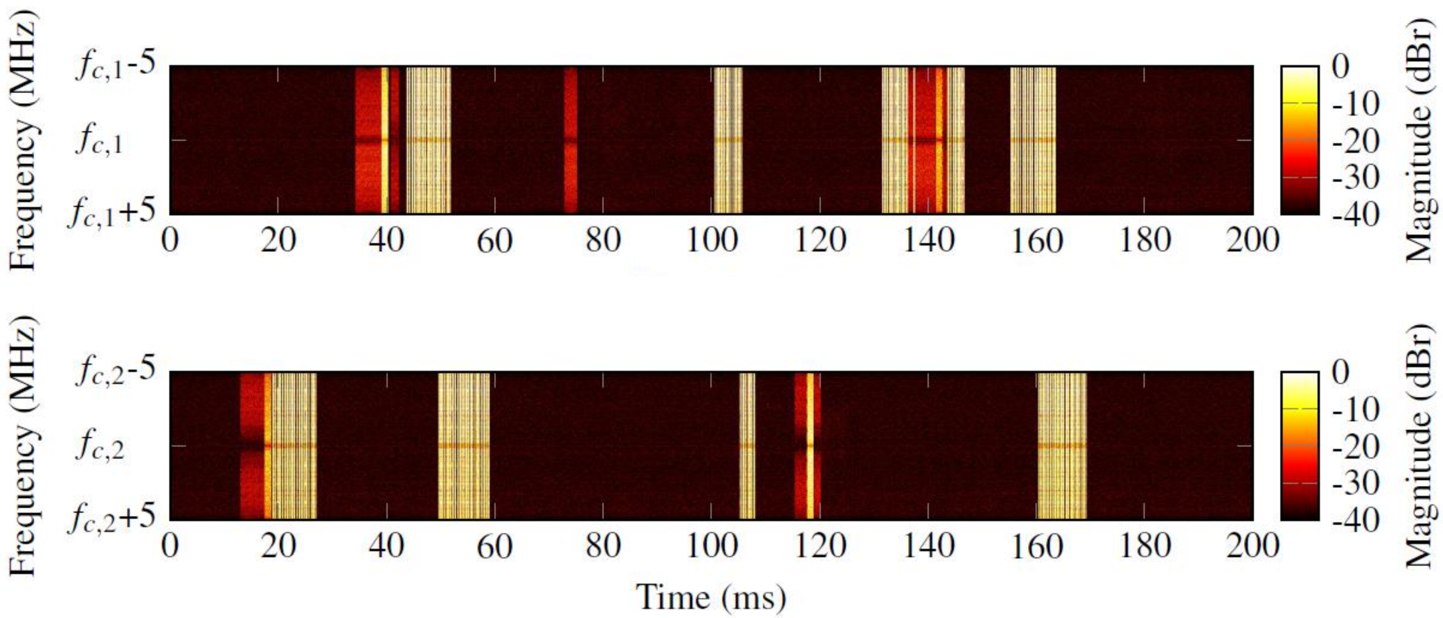
- **Focussing on Interferences caused by WLAN IEEE 802.11b/g**
  - Laboratory environment at FAU
  - Non-overlapping channels in 2.4 GHz ISM band
    - $f_{c,1} = 2.412\,\text{GHz}$ (Ch. 1)
    - $f_{c,2} = 2.437\,\text{GHz}$ (Ch. 6)
- **Measurement Platform**
  - Configuration of receivers
    - Carrier frequency: $f_{c,1}, f_{c,2}$
    - Sampling rate: 10 MSps
    - Reference level: -50 dBm
  - Acquisition of I/Q samples



3. Measurements

For Coexistence Analysis in the 2.4 GHz ISM Frequency Band

- **Results**
  - Spectrogramm



→ Measured I/Q samples (channel utilization) used for coexistence analysis

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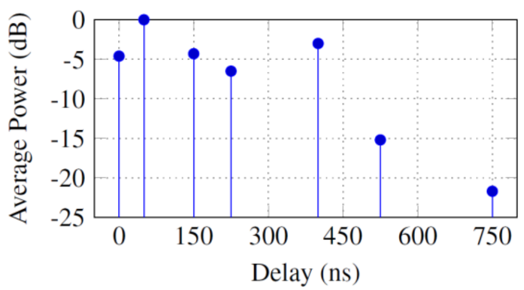
4. Evaluation

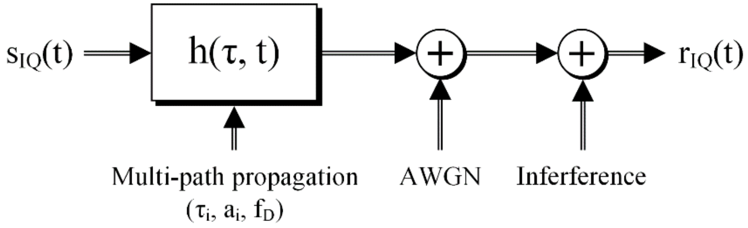
System Implementation / Configuration

- **MATLAB Implementation**
  - IEEE 802.11p PHY, SSU and MAC
- **Wireless Channel Emulation**
  - Multi-path propagation + AWGN + interference
  - Standardized Rayleigh model
    - JTC[1] (type indoor commercial B) [15]
- **Measured Channel Utilization in the 2.4 GHz ISM Frequency Band used for Coexistence Simulation**

Discrete Power Delay Profile



Baseband Wireless Channel Model

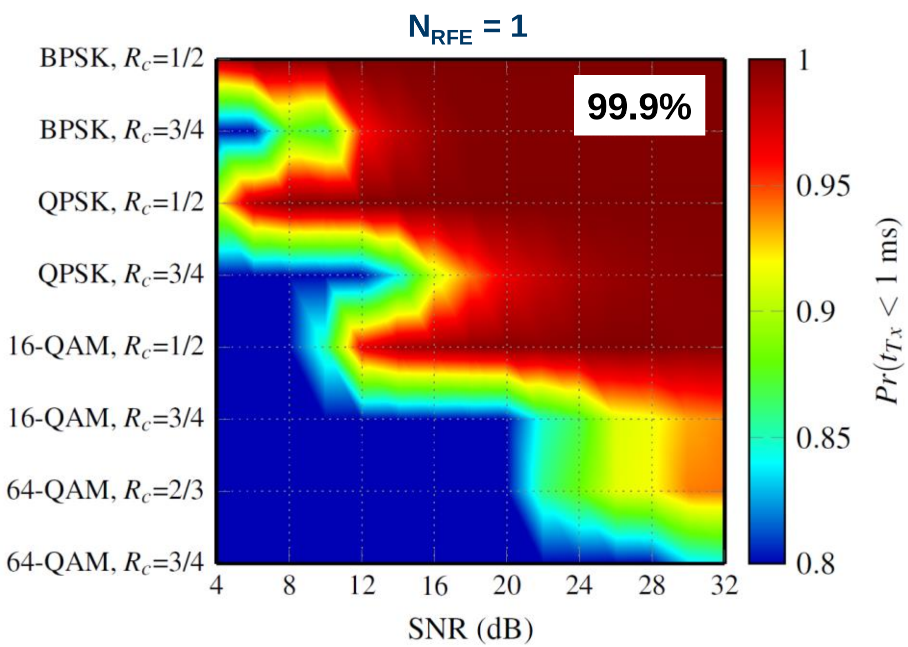


1) JTC = Joint Technical Committee

4. Evaluation

Simulation Results

- **Short-Real-Time Capability** $Pr(t_{Tx} < 1\ \mathrm{ms})$
  - Without interference



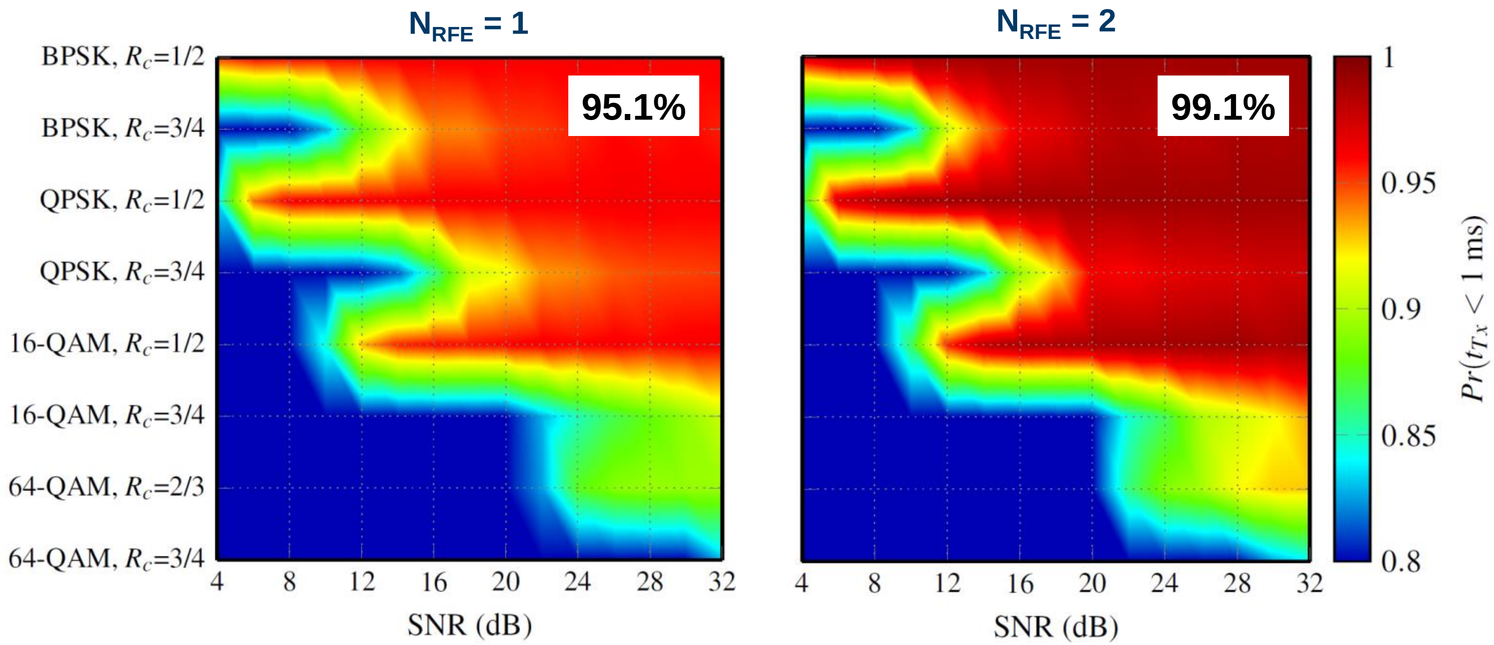
- P2P[1] communication scenario
- Payload of 50 bytes
- 2000 time slots per simulation step
- Evaluation of transmission probability during a time slot ($T_{Slot} = 1\ \mathrm{ms}$) in the 2.4 GHz ISM band
- Reduced performance due to transmission errors at low SNR[2]
- Highest performance with R_c = 1/2

[1] P2P = Point-to-Point
[2] SNR = Signal-to-Noise-Ratio

4. Evaluation

Simulation Results

- **Short-Real-Time Capability** $Pr(t_{Tx} < 1\text{ ms})$
  - With interference



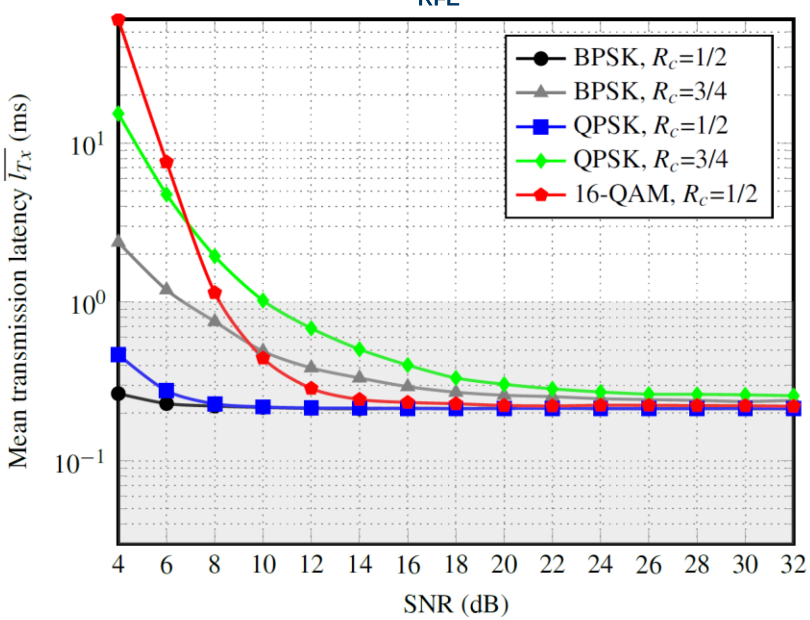
→ Performance degradation due to spectrum sharing → limited D-DSA

4. Evaluation

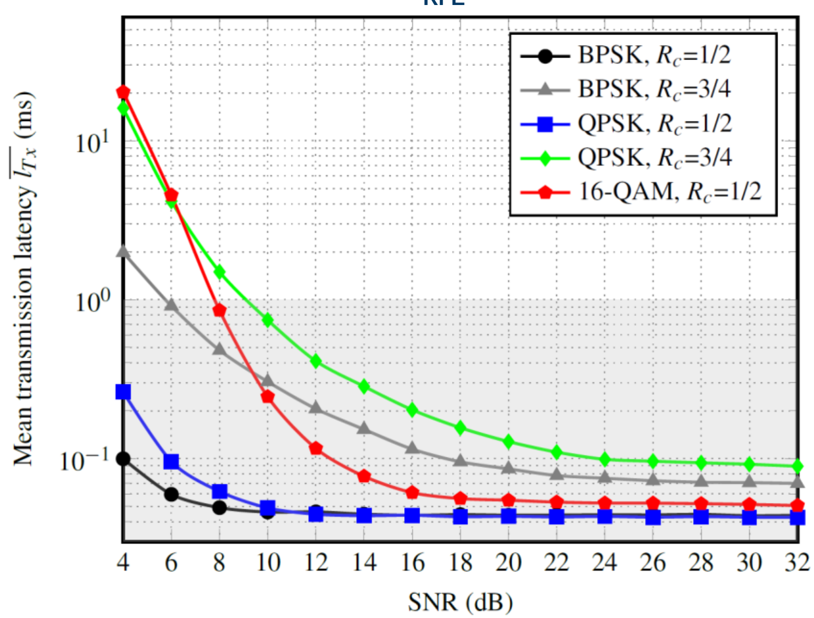
Simulation Results

- **Mean Transmission Latency $\overline{t_{Tx}}$**
  - With interference

N_{RFE} = 1



N_{RFE} = 2

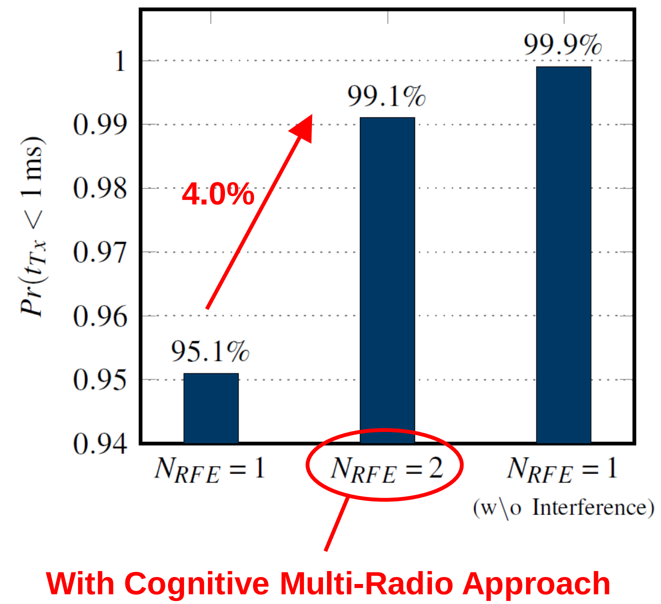


→ Reduction of $\overline{t_{Tx}}$ by a factor >2

4. Evaluation

Discussion

- **Pro**
  - Improvement of D-DSA in ISM bands
  - Improvement of short-real-time capability for wireless transmission of process data with stringend timing requirements ($T_{Slot} = 1\ \mathrm{ms}$)



- **Contra**
  - Higher hardware cost
    - Primary due to multiple RFEs
  - Higher energy consumption
    - Due to spectrum sensing and receiving with multiple RFEs

→ Focus of this work on improvement of short-real-time capability of IWC

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5. Summary

- **Requirements of IWC Systems**
- **Problems / Limitations of current IWC Systems**
  - D-DSA in coexistence-afflicted ISM frequency bands
  - Current IWC technologies do not provide short-real-time capability
- **Approach for Improvement of D-DSA in ISM Bands**
  - Transceiver concept → Cognitive Multi-Radio
  - Spectrum access scheme (compliant to ETSI EN 300 328 V1.9.1)
  - Markov-based channel modelling incl. channel selection strategy
- **Evaluation**
  - Improvement of D-DSA for short-real-time IWC

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Thank You for Attention!

Any Questions?

?

Appendix

Outline

- **Optimization of Channel Selection Strategy / Prediction Algorithm**
  - Further improvement of short-real-time capability in ISM bands

- **Hardware Demonstrator**
  - Based on Software-Defined Radio (SDR)
  - Conceivable SDR platforms
    - Nutaq ZeptoSDR (low-cost)
    - Vector signal transceiver NI PXIe-5645R (high performance)
  - Short-real-time characterization of proposed IWC system by measurements

Appendix

Second Use Case

- **Wireless Transmission of Automotive Diagnostics (UDS) and Control / Calibration Data (XCP) for Hardware-in-the-Loop (HIL) based Test and Verification of Electronic Control Units (ECUs) → Wireless Gateway (GW)**