Evaluation of Deterministic Medium Access Based on a Cooperative Cognitive Radio Approach

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***Abstract* — Caused by increasing demands for wireless devices in the last decade, license-free bands such as the 2.4 GHz ISM band become more and more crowded. As a consequence, interferences are inevitable. To avoid impairments caused by interferences, there have to be mechanisms to prevent coexisting systems to interfere with each other in license-free bands. Especially in industrial application fields, a reliable and deterministic medium access is required. In this paper, we evaluate an inter-system cooperation approach, which is designed to be aware of interferences, to ensure reliable real-time communication and further to protect investment for existing wireless systems. In a selected industrial scenario, it outperforms a non-cooperative approach especially in presence of interference. Further, it ensures a reliable communication for more than 99% of the real-time data packet transmissions also in presence of interference.**

Keywords - cognitive radio; control channel; deterministic medium access; inter-system automatic configuration

I. INTRODUCTION

*Cognitive radio (CR), "*firstly introduced by Joseph Mitola in 1999, is an emerging concept in the world of wireless communication" [1]. CR system is aware of its radio environment and therefore, detects interfering radio devices, which are called primary users (PUs). CR also identifies temporal and spectral opportunities for secondary user (SU) utilization. However, such prediction-based opportunity identification are prone to errors. Therefore, providing a deterministic medium access approach, which is able to be aware of its radio environment and to manage spectrum efficiency is highly desirable for CRs.

These solutions are also enablers for new industrial automation (IA) applications. IA applications require deterministic wireless medium access for reliable operation in real-time applications. As many wireless technologies – also for IA applications – share the same wireless channels such as the 2.4 GHz ISM band, a proper coexistence behavior is a fundamental requirement.

In this work, a proposed cooperative CR approach [2] is implemented and evaluated, which is called inter-system automatic configuration (ISAC). To the best of our knowledge, the proposed approach has not been implemented or evaluated yet.

ISAC's design has mainly three goals:

a) Interference awareness
b) Ensuring real-time and reliable communication
c) Investment protection for existing wireless systems

The first goal is necessary for IA applications to provide the second goal, real-time performance and reliable communications. ISAC systems aim to avoid interference with other wireless systems and protect themselves from being interfered.

The third goal focuses on implementation requirements. The ISAC approach unifies the spectrum utilization management. It is suitable for being integrated into existing industrial wireless solutions such as industrial WLAN, Bluetooth, WirelessHART, ISA100.11A, and ZigBee. The integration of the approach shall be therefore simple with minor protocol adaption.

This paper is organized as follows: Section II summarizes fundamentals about medium access and control channel usage. Section III illustrates the ISAC approach. Section IV specifies a selected measurement scenario, which is used for experimental evaluation. Section V analyses the results, and discusses the outcome. Finally, Section VI provides a conclusion for this paper.

II. STATE OF THE ART

IA applications provide harsh requirements for medium access methods (MAMs). To fulfill the requirements a cooperative approach among the users sharing the same environment with a proper controlling is necessary. A control channel (CC) is mandatory for this approach. In this section, the key issues MAMs and CCs are discussed in more detail.

A. *Medium Access Methods*

Multiple wireless devices utilize shared spectral, temporal, spatial resources. Therefore, wireless MAMs are approaching the issue of coexistence in different ways. They can be categorized into non-adaptive MAMs, adaptive MAMs, and cognitive MAMs [2][3]. They are briefly described in the following subsections.

1) *Non-Adaptive Medium Access Methods*

Non-adaptive MAMs use for example time-, frequency-, and code-division multiple-access (TDMA, FDMA, CDMA) [4]. They do not include any mechanism to mitigate interference and rely on central planning by a dedicated device or manual configuration. Due to their synchronous structure, non-adaptive MAMs require only a little communication overhead. Radio systems based on these MAMs provide a deterministic medium access in case of no interference. They are not aware of interference and therefore, show a poor coexistence behavior.

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2) *Adaptive Medium Access Methods*

While non-adaptive MAMs show poor coexistence behavior, adaptive MAMs are aware of the radio environment. They are aware of the radio environment to a certain degree to improve the performance. Examples of such methods are carrier sense multiple access with collision avoidance (CSMA/CA) [4], ALOHA [5], and adaptive frequency hopping (AFH) [6].

Adaptive MAMs mitigate interference with others in order to approach error-free transmissions. On the other hand they have no deterministic behavior. Thus, adaptive MAMs require a communication overhead and additional synchronization effort. Adaptive MAMs can be distinguished with respect to the feedback instant of time: Listen-before-talk (LBT) [4] and listen after talk (LAT) [4]. LBT requires feedback before transmission. Such a medium access mechanism is CSMA/CA. If no new interference appears during transmission, LBT MAMs will ensure an error-free transmission.

In contrast to LBT MAMs, LAT MAMs react on a feedback instant of time after packet transmission. Typically, they are based upon service degradation such as packet reception failure. An example is Bluetooth AFH. After some packet loss in a certain frequency channel, it will be avoided for further packet transmissions by channel blacklisting for a specific time duration. Because LAT MAMs react after packet transmission, they cannot guarantee error-free transmissions.

3) *Cognitive Medium Access Methods*

Adaptive MAMs have a reactive nature. In contrast, cognitive MAMs are based on proactive approaches. They try to model the radio environment and adapt the wireless communication accordingly in order to improve the transmission performance and increase the spectrum efficiency. They can be classified into autonomous and cooperative approaches.

Autonomous CR systems improve the performance of a single radio system opportunistically. While, cooperative systems negotiate the resource allocation and optimize the performance of several systems in a certain environment. This negotiation requires a communication opportunity, which can be achieved via a control channel (CC).

B. Control Channel

The CR needs to sense the spectrum and select an appropriate channel for the SU communication. To achieve this, cooperative CRs communicate with each other via a CC [1]. Basically, the CC is a logical channel. Its implementation offers two possibilities:

1) Common control channel: The control messages are being exchanged on the same channel as used for the wireless solutions but during idle data phases. This solution is easy from a hardware point of view but requires a sophisticated time scheduling, which might conflict with desired real-time application.

2) Dedicated control channel: A separate physical channel is reserved for the exchange of control messages. Depending on the available hardware structure, the dedicated CC might use the same transceiver unit as the data messages. As mentioned before, the same sophisticated time scheduling is necessary. If two transceiver units for the data and control messages are available, the time scheduling is drastically simplified.

A separate transceiver unit might also support a wired CC if the application tolerates it. Further examples are given in [7].

III. INTER-SYSTEM AUTOMATIC CONFIGURATION

The cooperative ISAC concept was published in [2] as work in progress. This paper contributes ISAC's implementation aspects, its evaluation and comparison with other approaches. The ISAC network consist of two different entities: ISAC supervisor and ISAC client. The ISAC network requires a single central ISAC supervisor and permits multiple ISAC clients. The ISAC supervisor uses the CC for communication.

A. Supervisor

The most important entity in an ISAC network is the ISAC supervisors for resource management.

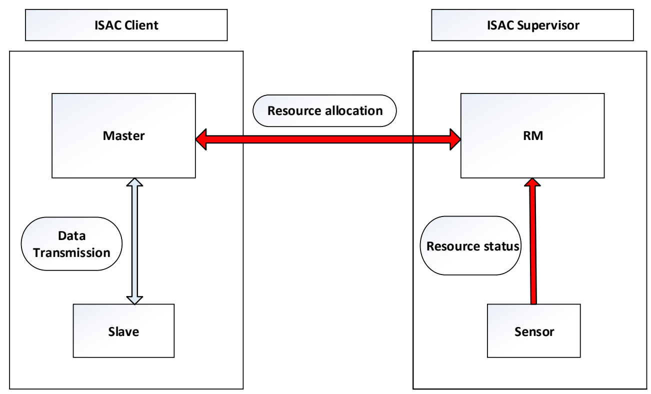

Figure 1. Basic ISAC network consist of ISAC supervisor and ISAC client connected via control channel (red arrows)

Thereby, the term resources refers to the hyperspace introduced in [8] consisting of multiple dimensions such as spectrum, time, code and the spatial dimension. The tasks of the ISAC supervisor are (i) resource allocation and (ii) interference mitigation. Therefore, it is equipped with the CR features of resource sensing and resource occupancy prediction.

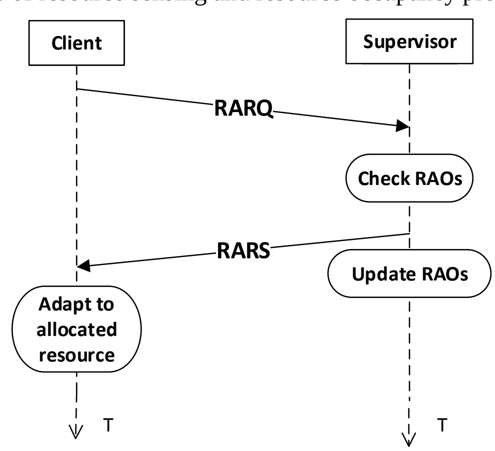

Figure 2. Sequence diagram of resource allocation negotiation between ISAC client and ISAC supervisor

As shown in Figure 1, the ISAC supervisor consists of two different wireless devices: Resource sensing device (sensor) and resource management device (RM). The sensor is responsible for resource sensing and predicting future behavior. Figure 2 shows the resource allocation negotiation procedure for two client. In case an ISAC client requests a resource allocation (RARQ), the RM selects the optimal resource allocation opportunity (RAO) according to the resource utilization capabilities of the ISAC client. Next, the RM response with the allocated resources (RARS) and the ISAC client tunes accordingly.

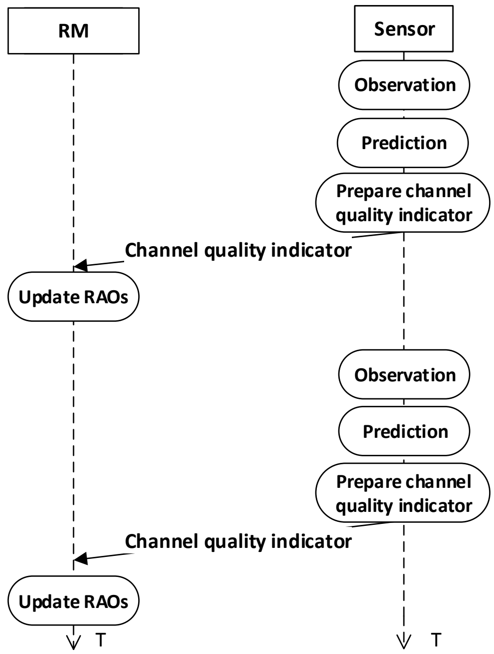

Figure 3. Sequence diagram of cyclic resource status reporting from sensor to resource manager

Additionally to resource allocation, the ISAC supervisor has to mitigate interferences, which could be either observed by the ISAC client or the ISAC supervisor's sensor. The sensor informs the RM about the resources status based on the resource sensing and prediction outcome. Then, the RM determines RAOs as illustrated in Figure 3. In case an ISAC client detects an interference within its utilized resources, it initiates a resource allocation negotiation within the limited resource utilization capabilities.

B. *Client*

The ISAC clients are resource users. The ISAC clients are independent wireless systems. In IA such wireless systems are Bluetooth piconets, WirelessHART mesh networks, or WLAN infrastructure networks. These wireless systems are used already for multiple applications like controlling or monitoring tasks. Each ISAC client has to provide a communication interface to the central ISAC supervisor. Typically, a good choice for the integration is the central management device of the certain wireless system like Bluetooth master, WirelessHART gateway, or WLAN access point, respectively.

The ISAC client's tasks are to (i) request for resource allocations from the ISAC supervisor and tune accordingly, and optionally to (ii) inform the ISAC supervisor about interferences. In order to reach the first task, the only mandatory requirement for the ISAC clients is to have tuning capabilities.

In order to reach the optional second task, the ISAC clients have to be equipped with sensing capabilities either listen-before-talk features such as WLAN and WirelessHART CSMA/CA or packet loss notification features. The sensing outcome can be used to initiate a resource allocation negotiation as mentioned above.

C. *Control Channel*

The ISAC CC is used for the communication between the ISAC supervisor and ISAC clients, and within the ISAC supervisor between RM and sensor. Further, the ISAC concept requires a dedicated CC, which has to be always available for communication. So, it has to be guaranteed that the CC never gets interfered by some PUs, SUs or any other kind of interferences.

IV. IMPLEMENTATION

The introduced general ISAC concept is implemented and evaluated within an IA scenario. The specific ISAC network setup is shown in Figure 4.

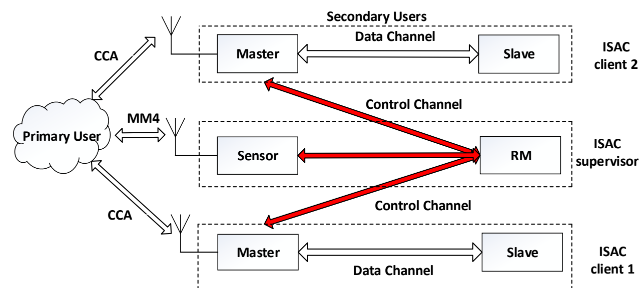

Figure 4. Measurement setup with interfering PU and SU containing an ISAC network with two ISAC clients

The master uses a frequency channel called data channel (DC) for data transmissions to its slave. Three frequency channels are available for data transmission. These three channels are named CH1, CH2, and CH3. These are the available spectral resources. Hence, the implementation is limited to spectral resources and does not consider the management of other resources such as temporal, code or spatial resources.

Another type of frequency channel is the dedicated CC, which is named CH0. For simplicity reasons, we assume that CH0 is not interfered by any primary user. In the following sections the SU and PU setups are discussed.

A. *Secondary User Setup: ISAC Clients*

In order to address a crowded IA scenario, we evaluate the ISAC network with two ISAC clients. Both ISAC clients are independent wireless systems performing real-time data transmission tasks. In order to lower the network implementation complexity, both ISAC clients are operating identically in a master-slave constellation, which is common in IA scenarios.

The master and slave are implemented in the microcontroller MSP430 of Texas Instruments (TI) with the narrowband transceiver CC2500. The master transmits data packets of fixed size and content while the slave returns the received data

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packets to acknowledge the correct reception. Important features and selected time parameters are summarized in Table I.

TABLE I: SU ISAC CLIENT MASTER AND SLAVE TEST-BED FEATURES

Platform	µC MSP430 with transceiver CC2500			
Channel	CH0	CH1	CH2	CH3
Center frequency	2.43 GHz	2.44 GHz	2.45 GHz	2.46 GHz
Channel Type	CC	DC	DC	DC
Spectrum sensing	No	RSSI-based CCA prediction		
Sample time	-	~ 90 µs		
Traffic	RARQ	Real-time data transmission		
Type	Event-based	Cyclic		
Period	-	40 ms		
Acknowledgment	-	Data echo		
QoS	No	PLR in %		
Packet duration	~1.2 ms	~2.7 ms		
Switching time	~ 100 µs			
Bit error detection	CRC-16			

Each ISAC client starts communication on the default DC. The master is equipped with the sensing feature listen-before-talk by a clear channel assessment (CCA) based on the received signal strength indication (RSSI) within its current DC. In case of successful CCA the data transmission is continued in the current DC. Otherwise the current DC is interfered by the PU or the other ISAC client. As shown in Figure 5, before next data transmission, the master tunes to the CC in order to initiate a resource allocation negotiation. The ISAC supervisor response with the new allocated DC. After receiving the response from ISAC supervisor, the master tunes to the previous DC in order to notify the slave about the new allocated DC. The master tunes to the new allocated DC, when the slave successfully acknowledges (ACK) the notification. In case the notification is unsuccessfully acknowledged from slave, the master continues sending notification till receiving successful acknowledged from slave.

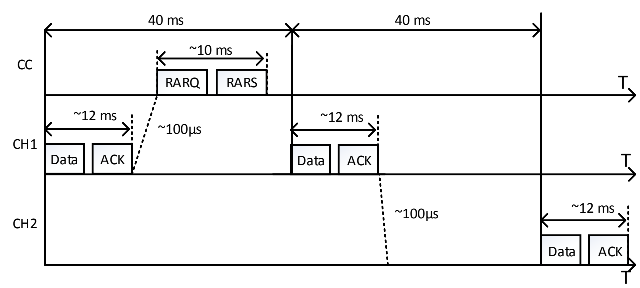

Figure 5. Timing diagram of master-slave resource allocation change within real-time data communication

The master does not stop data transmission during resource allocation negotiation. In case of resource allocation negotiation between master and supervisor failure, the master will tune to previous DC and will try to continue data transmission. With the next CCA failure, the master initiates a new resource allocation negotiation with ISAC supervisor. Therefore, the master does not lose any data transmission. The master performs the CC communication within its idle time. As a consequence, data transmission is always in real-time.

B. *Secondary User Setup: ISAC Supervisor*

The ISAC supervisor contains the sensor and the RM specified in Table II and Table III, respectively. The sensor and RM are also implemented in the microcontroller TI MSP430 with the narrowband transceiver TI CC2500.

TABLE II: SU ISAC SUPERVISOR SENSOR TEST-BED FEATURES

Platform	µC MSP430 with transceiver CC2500
Channel type	CC
Center frequency	2.43 GHz
Data packet duration	~1.2 ms
Bit error detection	CRC-16
Spectrum sensing	MM4-based DCs occupancy prediction
Acknowledgment	No
Traffic type	Cyclic
Idle time	30 ms
Duty cycle	~4 %
Period	~31.2 ms

The sensor senses all DCs periodically. Then, it determines two measures derived from the Markov model MM4 published in [2][9]. The first measure is the busy distance expressing the observed mean count of consecutive occupied samples within a certain DC, which are interfered by PUs. The second measure is the idle distance expressing the mean count of consecutive non-occupied samples, respectively. Based on the difference between the busy and idle distances, the DCs are sorted according to their quality. This information is given to the RM as DC quality indicators. Hence, the DC quality indicators provide information about the amount of interference of each DC.

TABLE III: SU ISAC SUPERVISOR RESOURCE MANAGER TEST-BED FEATURES

Platform	µC MSP430 with transceiver CC2500
Channel type	CC
Center frequency	2.43 GHz
Data packet duration	~1.2 ms
Bit error detection	CRC-16
Traffic	RARS
Type	Event-based

The RM has the responsibility to update the RAO. Therefore, it stores the very last DC quality indicators permanently. Hence, upcoming resource allocation decisions are based on the last stored DC quality indicators.

C. *Primary User Setup*

TABLE IV: PU TEST-BED FEATURES

Platform	Vector Signal Generator SMBV100A
PU type	Cyclic IEEE 802.11g-like transmission
Center frequency	2.45 GHz
Data packet duration	~2 ms
TX power	15 dBm
Traffic type	Cyclic
Idle time	10 ms
Duty cycle	~16.7 %
Period	~12 ms

A selected PU activity is based upon IEEE 802.11g-like transmissions, which is common in IA scenarios. The PU activity is generated by a vector signal generator. Further important features and selected time parameters for the PU are summarized in Table IV. While the SUs are sensitive to the radio environment, the PU performs cyclic data transmission without feedback from the radio environment based on CSMA/CA. The PU is a single device, which transmits data packets with a duration of 2 ms and a period of 12 ms. It is important to note, that only CH2 is interfered by the PU.

V. Result and Analysis

In this section, we present the ISAC results in comparison to an appropriate reference.

A. *Implementation Validation*

The cyclic SU and PU emissions using ISAC are illustrated in the measured spectrograms in Figure 6 and Figure 7. The measurements were done with the real-time spectrum analyzer Tektronix RSA6114A. The horizontal and vertical axis represent the frequency and the time, respectively. CH0 is CC and CH1, CH2 and CH3 are the defined DCs.

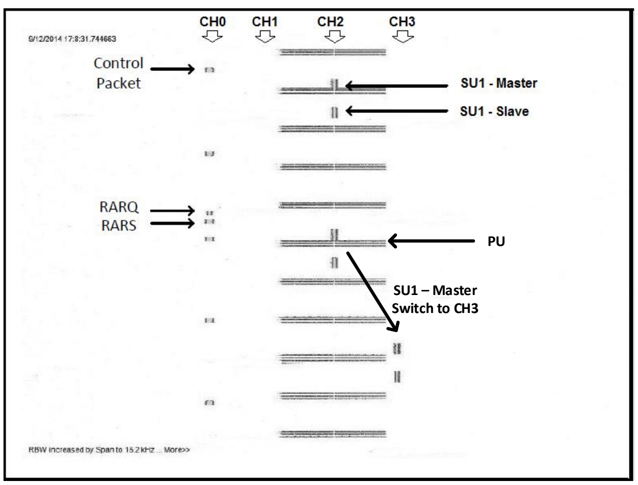

Figure 6. Spectrogram of the resource allocation negotiation with RARQ and RARS within the control channel of SU master and slave to avoid PU interference

The spectrogram ranges from 2.43 GHz to 2.48 GHz and has a duration of 100 ms.

Figure 6 shows the cyclic operation of the PU interfering CH2 where an ISAC client is transmitting data. This PU activity causes packet loss. The ISAC client detects PU activity and sends a RARQ to the RM. Then, according to RARS from the RM, the ISAC client tunes to the allocated free DC and therefore, bypasses future activity of the PU.In case of multiple ISAC clients, the RM allocates different DCs to each ISAC client while observing the PU interference.

As shown by the example in Figure 7, the PU interferes CH2 only while the ISAC clients transmit data in CH1 and CH3.

B. *Experimental Results*

For evaluation, we measured the QoS within two different scenarios, which differ in the presence of PU interference. Within each scenario, we performed experiments for three different medium access types: Non-sensing (NS), non-cooperative (NC), and ISAC-based medium access. The implementation of the latter one was introduced in Section IV.

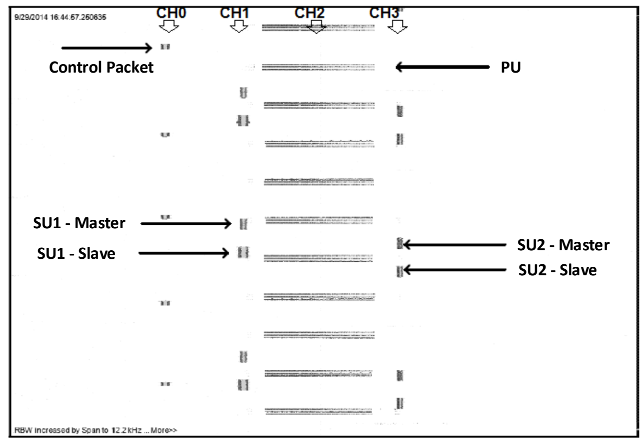

Figure 7. Spectrogram of two SU master-slave data transmissions within different frequency channels allocated by the resource manager

The NC medium access neglects the usage of the cooperative ISAC concept. I.e. each SU client works independently. In this setup, the master performs a CCA based on MM4 before each data transmission in the default DC CH2 as published in [2][9]. In case of CCA failure, the master switches to the backup DC CH3 after informing the slave. Hence, they try to omit the backup DC as much as possible.

The NS medium access even reduces the complexity of the non-cooperative medium access. The master does not sense the spectrum in terms of any CCA. Therefore, it is not able to predict spectrum occupancy or to detect PU interference. The master does not tune to any other channel either. Hence, there will be data transmission collisions and packet loss. The experiments are performed with a measurement duration for 1000 data packet transmissions, which are repeated 5 times and are averaged to result in a representative evaluation. Thereby, the master of both real-time wireless systems for each experiment determines the packet loss rate (PLR) as a measure of QoS. For each failure in receiving the correct ACK, the master increase the number of packet losses. Figure 8 and Figure 9 show the result of all experiments in case of PU interference absence and presence, respectively. The horizontal and vertical axis represent the medium access types in different devices and the PLR, respectively in Figure 8 and Figure 9.

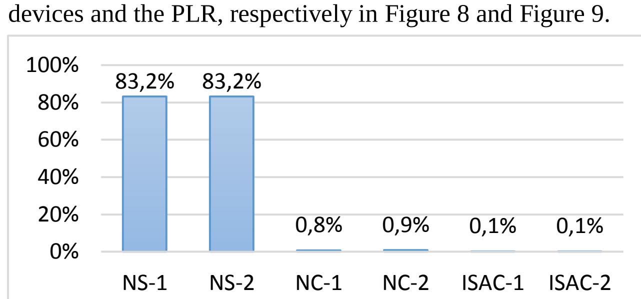

Figure 8. PLR (vertical axis) of two master-slave constellations (index 1 and 2) for the medium access methods (horizontal axis) non-sensing (NS), non-cooperative (NC) and ISAC in absence of PU

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They show the PLRs for both real-time wireless systems. Clearly, NS medium access has the worst performance in both scenarios. This results from its non-cooperative and non-adaptive medium access. In case of no PU interference, the two real-time wireless systems interfere each other.

The same disturbance can be observed also for the NC medium access but the PLR is below one percent without PU activity. The NC medium access avoids the PU interference much better than the NS medium access. However, the PLR is above 25% with PU activity.

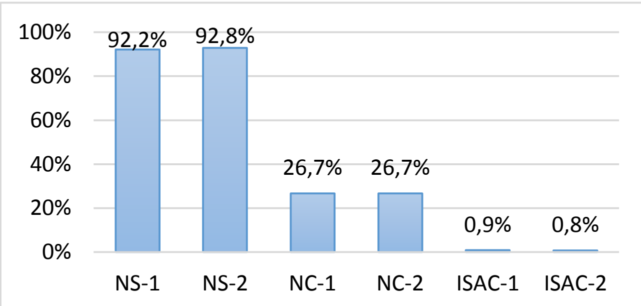

Figure 9. PLR (vertical axis) of two master-slave constellations (index 1 and 2) for the medium access methods (horizontal axis) non-sensing (NS), non-cooperative (NC) and ISAC in presence of PU

The best performance can be seen for the ISAC-based medium access. The PLR is below one percent even in presence of PU interference.

VI. Conclusion and Future Work

The paper introduces a cooperative cognitive radio approach implementation providing a deterministic medium access called inter-system automatic configuration approach (ISAC). Its performance is evaluated to face the increasing demands for industrial wireless devices in license-free bands. ISAC focuses on the industrial automation requirements of (i) interference awareness, (ii) ensuring real-time and reliable communication, and (iii) investment protection for existing wireless systems.

A central radio device manages the allocation of resources such as frequency channels, time slots and spatial resources in a cooperative inter-system manner to ensure reliable communication. Further, a sensing radio device reports the resource status continuously for awareness of non-cooperative wireless systems and other interferences in the radio environment. Additionally, each cooperative wireless system has to negotiate resource allocations and to notify interferences. Therefore, a single device has to be replaced or updated with an appropriate communication interface and configuration with adaption capabilities. This minor modification of existing wireless systems ensures investment protection. It is important to note that ISAC's central radio device communication is performed in a dedicated control channel.

The evaluations are done for a selected industrial scenario in a test-bed based on multiple radio devices with TI MSP430 microcontroller and TI CC2500 narrowband transceiver. Two industrial wireless systems with a real-time master-slave constellation are deployed and act as secondary users. They cooperate via the control channel with the central resource manager radio device. Thereby, three different frequency channels serve as resource opportunities, which are partly interfered by a non-cooperative primary user. The primary user represents an infrastructure-based IEEE 802.11 wireless system often applied in factory automation. The interferences are sensed and reported via a control channel in terms of frequency channel occupancy prediction with an additional radio device.

To show the benefits of cooperation, ISAC's performance is compared with a (i) non-cooperative and with a (ii) non-cooperative non-sensing approach, which are also introduced and explained in detail. Thereby, ISAC outperforms both approaches especially in the presence of primary user interference. Hence, cooperation increases interference awareness significantly. Further, ISAC ensures a reliable communication for more than 99% of the real-time data packet transmissions independently of primary user interference presence. Hence, reliable communication can be ensured.

Further investigations shall advance the resource allocation to multiple dimensions such as time and spatial resources. Additionally, hybrid allocation schemes mixing central and distributed decision-making may be evaluated to lower latency especially for temporal resource allocation without losing the benefits of central management. Also, the evaluation of a common control channel may be investigated, which shares the same licensed-free band for convenience reasons and further investment protection.

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