Wireless Deterministic Medium Access: A Novel Concept Using Cognitive Radio

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***Abstract*—The growing demand for coexistence of wireless systems in industrial automation applications must be met by a implementation of a deterministic medium access. Therefore, we propose a novel concept which is based on inter-system communication. It optimizes spectrum efficiency by handling resource reservations in the frequency and time domain. It is also aware of its environment by cooperatively mitigating interferences. Further, it requires only minor modifications of existing wireless solutions.**

Keywords-deterministic medium access. cognitive radio. control channel. inter-system protocol

I. Introduction

The demand for wireless devices has been continuously growing in the last decades. Especially license-free bands such as the 2.4 GHz ISM band become more and more crowded. The range of application fields rises for wireless devices, too. Some application fields are mobile telephones, remote control, monitoring, notification services, Internet access and multimedia streaming. Many high data rate application demands will arise in the near future due to trends like the so called smart-phones. It creates a need for the coexistence of license-free bands.

The growing demand in consumer applications decreases the costs of standard components such as wireless transceivers. Thus, the number of wireless solutions increases also for industrial automation (IA) applications. Wireless solutions enable monitoring and controlling tasks for long distances and hard-to-reach locations. They also decrease the dependence on expensive, failure-prone wired connections and replace outwearing sliding contacts.

Wireless solutions are also enablers of new IA applications with even more challenging requirements for coexisting license-free bands. They require a deterministic medium access and data transmission behavior. However, currently the license-free bands do not guarantee any specific medium access.

In this work-in-progress paper, we propose a novel cognitive radio approach focusing on IA. The approach has mainly three goals:

1) To provide a deterministic medium access,
2) To apply only minor modifications to existing wireless solutions especially to all slave nodes, and
3) To be aware of its environment.

The first goal is necessary for IA applications to ensure real-time performance and reliable communication. In addition to IA applications, a deterministic medium access improves security application.

The second goal focuses on low implementation requirements. While only few devices require the usage of a new protocol, most devices do not need any additional functionality. They use their protocol-specific interference reporting functionality such as packet loss notification in a specific time slot and channel. Hence, most of the existing and widely used wireless systems only require an adaption of the master device such as an access point in case of an IEEE 802.11 system [1].

Finally, the approach targets environmental awareness – the third goal. Hence, it does not interfere with other detectable and predictable wireless systems but protects itself from being interfered. The interference mitigation is performed for several dimensions such as time, frequency and space.

The paper is structured as follows: Section II discusses the three categories of medium access methods: non-adaptive, adaptive and cognitive. In Section III the novel medium access method and its three components (the supervisor, the clients and the control channel) are introduced. Finally, Section IV discusses open issues and Section V concludes the paper.

II. Medium Access Methods

The coexistence requirements for wireless communication raised the number of medium access methods (MAMs). There are

- Non-adaptive MAMs,
- Adaptive MAMs and
- Cognitive MAMs.

These are described in the following sections.

A. Non-adaptive Medium Access Methods

Non-adaptive MAMs are for example multiple access methods such as time-, frequency- and code-division multiple-access (TDMA, FDMA and CDMA) [2]. They do not include any mechanism to mitigate interference

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but rely on central planning by a dedicated device or on manual configuration. Due to their synchronous structure, non-adaptive MAMs require only a little overhead of communication. In consequence, it is easy to implement and to provide a deterministic MAM. However, they do not adapt to the environment by ignoring interference but interfere with others. Due to such drawbacks it is advisable to use adaptive MAMs.

B. Adaptive Medium Access Methods

While non-adaptive MAMs represent straight forward approaches, adaptive MAMs are aware of the radio environment. They react to a feedback from the radio environment to mitigate packet loss. Such methods are for example ALOHA [3], carrier sense multiple access with collision avoidance (CSMA/CA e.g., applied in IEEE 802.11 DCF [1]) and adaptive frequency hopping (AFH e.g., applied in Bluetooth [4]).

Adaptive MAMs mitigate interference with others and ensure error-free transmission. On the other hand they have no deterministic behavior. Thus, adaptive MAMs require an overhead of communication and/or synchronization. For example in CSMA/CA the receiver has to wait for an unknown and random period of time for packet transmission.

Further, adaptive MAMs can be distinguished with respect to the moment of feedback: Listen before talk (LBT) and listen after talk (LAT) MAMs. LBT requires feedback before transmission. Such a MAM is for example CSMA/CA. It senses the channel before transmitting. Hence, if the channel is classified as idle a permission for packet transmission is provided. The adaption of LBT MAMs is based on the current state of the channel. If no new interference appears during transmission, LBT MAMs will ensure error-free transmission.

While LBT MAMs react on feedback before transmission, LAT MAMs adapt to new situations. This can be concluded from the evaluation of previous transmissions. In this context AFH is a good case in point. AFH is based on the spectrum spreading technique FHSS, which switches – called hopping – between multiple non-overlapping narrow-band frequency channels in a (pseudo) random manner. If there is a packet loss in a specific channel, AFH will block the channel for future use. The adaption of LAT MAMs basically depends on the state of the channel for previous transmissions. Therefore, LAT MAMs are not able to guarantee error-free transmission, even if no new interferences appear during data transmission.

C. Cognitive Medium Access Methods

Although adaptive MAMs improve the quality of transmission by mitigating interference, they suffer from the system centric approach and missing abilities to collaborate in any way with different systems. In consequence, adaptive MAMs are suboptimal for inhomogeneous radio environments. Collaboration would improve the efficient usage of spectrum, time and space. Further, collaboration reduces overlapping resource allocation.

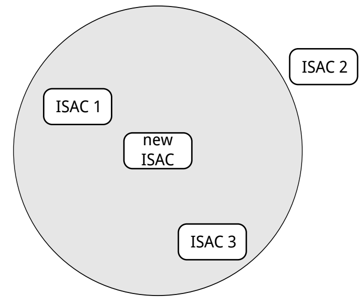

Figure 1. Example coverage range of the system ”new ISAC”

MAMs which are aware of their environment – more than only by adaption – can be called cognitive MAMs. They are not limited to collaborative approaches. Cognitive MAMs in general adapt to the environment by sensing channels, predicting channel occupancy, negotiating sensing information and transmission parameters, and adequate tuning. Further, cognitive MAMs are able to adapt themselves flexibly in more than one dimension (e. g. time, frequency and space).

III. Inter-System Automatic Configuration Method

We propose a novel MAM called inter-system automatic configuration MAM (ISAC MAM). The approach is operating between systems. A system is for example a wireless network based on IEEE 802.11 with one access point and several stations. For proper operation ISAC has to be supported by each system operating in the same frequency band.

Each system consists of several types of devices. From the ISAC MAM point of view, system devices are either ISAC supervisors or ISAC clients. An ISAC supervisor is a dedicated device which performs processes and negotiations. An ISAC client includes only minor supporting and adapting tasks. Each system must have one ISAC supervisor while having an unspecified number of ISAC clients. The communication between ISAC supervisors is done via a dedicated channel called ISAC control channel.

A. Supervisor

The most important device in an ISAC MAM system is the ISAC supervisor. It has two main tasks: (i) to handle resource allocation and (ii) to mitigate interferences. Resource allocation is performed by *resource allocation negotiation* and by *resource reversion negotiation*. In the following we discuss the tasks of an ISAC supervisor for an IEEE 802.11 (WLAN) system as example.

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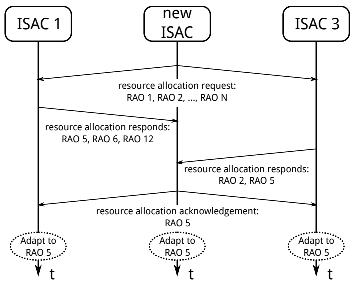

Figure 2. ISAC resource allocation negotiation

Table I
EXAMPLES OF RESOURCE ALLOCATION OPPORTUNITIES

Opportunity No.	Dimension	Unit	Type	Value
	Frequency	MHz	Minimum	2402
1	Frequency	MHz	Maximum	2422
	Time	%	Duty cycle	100
	Frequency	MHz	Minimum	2407
2	Frequency	MHz	Maximum	2427
	Time	%	Duty cycle	100
...				

Resource Allocation Negotiation: If a new ISAC supervisor requires resources, it has to initiate a *resource allocation negotiation*. The negotiation principle is illustrated in Fig. 2.

First, the initiating ISAC supervisor has to broadcast a *resource allocation request*. This message also contains a list of resource allocation opportunities (RAO). The RAOs are limited in each dimension (see Table I). Each RAO is associated with a specific operation mode of that particular system. Hence, the RAO 1 is associated with WLAN channel 1 and RAO 2 with WLAN channel 2.

All ISAC supervisors in the coverage range (see Fig. 1) participate in the negotiation. After receiving the request, they check which RAOs are not conflicting with their own operation or to which RAOs their operation is able to adapt while proper operation will be guaranteed. The identifiers of the coexistence capable RAOs are sent to the initiating ISAC supervisor with the *resource allocation responds*.

After receiving all responds, the initiating ISAC supervisor has to choose the optimal RAO. An optimal RAO is permitted by all ISAC supervisors. The initiating ISAC supervisor broadcasts a *resource allocation acknowledgement* containing the identifier of the optimal RAO.

Finally, the initiating ISAC supervisor informs its own system about the optimal operation mode. If necessary, the other ISAC systems also adapt their operation mode. The chosen optimal RAO is considered allocated until it is reverted or until the associated ISAC supervisor is no longer accessible.

Resource Reversion Negotiation: If some resource allocation is no longer needed, an ISAC supervisor can revert the allocation by performing a *resource reversion negotiation*. The principle is illustrated in Fig. 3.

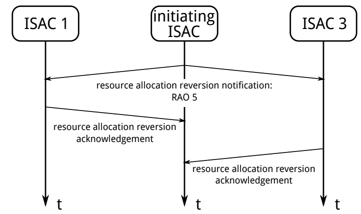

Figure 3. ISAC resource reversion negotiation

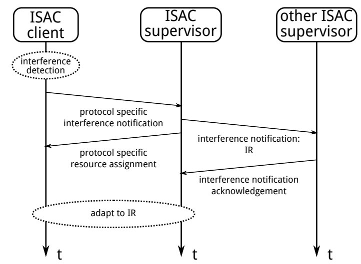

Figure 4. ISAC interference notification

The initiating ISAC supervisor broadcasts a *resource allocation reversion notification* containing the concerned RAO. The ISAC supervisors in the coverage range acknowledge the notification with a *resource allocation reversion acknowledgement*. Then the resource allocation is canceled and it is no longer considered allocated.

Interference Notification: The second main task of an ISAC supervisor is to mitigate interferences. The source of an interference may be an unknown wireless system. It may also be an ISAC system which is out of the ISAC supervisor's coverage range, but close enough to disturb the communication of the ISAC system (see ISAC 2 in Fig. 1). An interference can be observed by the ISAC supervisor or even by an arbitrary ISAC client due to its cognitive features.

If an interference is observed, an ISAC system mitigates the interference and its ISAC supervisor informs other ISAC supervisors about the interference. This principle is displayed in Fig. 4. In case the ISAC client observes an interference, it informs the ISAC supervisor. This is done in the specific protocol used by the particular ISAC system (e. g. IEEE 802.11). The ISAC supervisor may detect an interference. Then the ISAC supervisor broadcasts an *interference notification*. The notification contains the interfered resources specification (IRS). IRSs use the same structure as RAOs but represent interfered resource specifications, which are also called black holes [5]. The notification is responded by an *interference notification acknowledgement*. Thus, if the informed ISAC supervisors want to allocate resources later on, they know the IRSs.

Additionally, the ISAC supervisors have to take care of their own system. Therefore the protocol specific adaptive

MAM is used. In our example the ISAC clients shall take care of the IRs by using CSMA/CA. In case some IRSs cannot be mitigated by protocol-specific adaptive MAMs, the ISAC supervisor has to initiate a *resource allocation negotiation*.

B. Client

An ISAC system contains one ISAC supervisor and an arbitrary number of ISAC clients. The ISAC clients do not use the control channel. Owing to the fact that they only have to communicate with the ISAC supervisor, the communication protocol is system-specific and therefore not part of this paper. Hence, in a WLAN ISAC system an arbitrary client communicates with its supervisor using IEEE 802.11 packet frames.

In order to detect interferences, ISAC clients should also be equipped with cognitive features. ISAC clients mainly have two tasks: (i) to adapt to resource assignment instructed by their ISAC supervisor and (ii) to inform their ISAC supervisor about interferences. While the first task is mandatory, the second one may be optional. These tasks has already been discussed in detail in the previous section.

C. Control Channel

The ISAC control channel is used for the communication between ISAC supervisors. Using a control channel is a well-known cognitive radio approach (see [6]). Therefore, the control channel is commonly reserved for ISAC supervisor communication. To guarantee proper operation the control channel always has to be available.

We consider that the ISAC control channel is in itself a specific wireless technology, although it is not necessary. In contrast to the conditions given in the context of wired communication, it is easy to setup such systems. They also allow for temporary radio systems such as adhoc inter-vehicular communication systems. However, the disadvantage is that the control channel might be temporarily not available, as in the case of non-deterministic interferences or due to degradation of radio propagation conditions. This problem can be solved by data redundancy and packet retransmissions.

While an ISAC system itself may use any specific protocol, the ISAC control channel uses a common protocol. The control channel also has to be a-priori known to avoid time-consuming discovery and synchronization techniques. Hence, the ISAC control channel cannot use cognitive MAMs.

Further, to enable fast varying network scenarios, the control channel itself cannot be managed in a centralized manner. For this reason, an optimal MAM is distributed and non-cooperative. Therefore, we suggest an adaptive MAM. To realize a non-cooperative approach LAT cannot be used. Thus, the optimal control channel is based on an adaptive MAM using LBT.

IV. Conclusion

In this paper, the growing demand for coexistence of wireless technologies, especially in license-free frequency bands, is met by the introduction of a new approach. The approach focuses on the requirements of industrial automation to ensure a deterministic medium access.

The approach handles inter-system reservation of resources such as frequency and time. In other words, it ensures efficient usage of available resources. In addition to resource reservation, it handles interference mitigation, cooperatively. Therefore, it is aware of the radio environment. Further, the approach brings only minor modifications to existing wireless solutions. Hence, the approach is also easy to implement.

The inter-system communication itself is performed via a fixed control channel. This control channel is also based on wireless communication. The control channel has to be constantly available. In some scenarious this could be a challenge. Further, we conclude that the optimal control channel shall use an adaptive medium access method of listen-before-talk type.

V. Future Work

This paper discusses a novel approach, which requires some future work. Most importantly, the protocol for the wireless communication of the control channel has to be specified. Further, sample implementations have to be provided and appropriate simulations have to be performed. The results shall be verified by measurements.

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