Non-Invasive Cognitive Radio for Firm Real-Time Sensor Applications in heterogeneous Radio Environments

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***Abstract*—Some applications in Sensor Networks need firm real-time support in order to work properly. The difference to hard real-time systems is that this type of application can withstand minor violations of the maximum delay and minimum throughput if these violations are limited. Many standards like IEEE 802.15.4 provide standardized means to ensure delay and bandwidth constraints which work well when there are no interferers in the same frequency band. However, in a heterogeneous environment today these approaches fail when the interference is not aware of the IEEE 802.15.4 traffic. Switching the channel is one option to avoid this kind of interference. We suggest a new non-invasive cognitive radio protocol approach where all participants follow simple rules to enable firm real-time conditions in decentralized design. As a demonstrator we use a three-fold pendulum with firm real-time signal delay constraints of 5ms. The contributions of the paper comprise evaluation results by real measurements with the demonstrator system.**

***Index Terms*—Wireless Sensor; Cognitive Radio; Firm Real-time; Protocol;**

I. INTRODUCTION

Today's radio standards were continuously improved and engineered in the past. Therefore, new fields of application for wireless systems are enabled [1]. Systems which were impossible to setup can now be implemented. Especially wireless control system can gain from this development. Real-time applications are one example for a new application area of wireless technologies. Such applications can be divided into hard, firm and soft real-time applications [2]. In hard real-time missing a single system deadline results in a total system failure. Firm real-time systems tolerate missing a deadline infrequently until a certain marginal degradation of the system performance. Soft real-time applications accept missing deadlines and the corresponding degradation of the system performance. In our work, we implement a firm real-time application, the control of a three-fold pendulum, as a demonstrator to evaluate the performance of our new developed non-invasive cognitive radio sensor protocol.

Another important effect of the successful radio standards is that more and more wireless systems are deployed for all kinds of applications. With this increasing utilization of radio links the available frequency spectrum becomes a scarce resource. One typical example for such a heterogeneous radio environment is the 2.4GHz frequency band, utilized inter alia by WLAN, Bluetooth and IEEE 802.15.4. Cognitive systems, also known as Cognitive Radios (CR), are currently under investigation [3], [4]. They are aware of the current radio environment and have the potential to reach coexistence of wireless systems even in the future within heterogeneous environments. Our approach uses CR techniques to detect concurrent radio links and adapt transmission parameters accordingly to avoid collisions and reach firm real-time characteristics.

Therefore, contribution of our work is threefold. First, we present a new non-invasive cognitive radio protocol for a sensor application with firm real-time requirements. Our solution is based on a decentralized rule based approach beyond existing reservation and synchronous Time Division Multiple Access (TDMA) schemes. Second, we provide solutions in a heterogonous radio environment by switching to free channels without an additional control channel. We detect own data packets, interfering packets using same wireless technology AND other interfering wireless technologies. Third, we present a firm real-time demonstrator based on 802.15.4 physical layer with delay requirements less than 5ms to evaluate and prove the effectiveness of the approach. To the best of our knowledge, this is the first time that such a non-invasive cognitive radio sensor protocol including demonstrator in such a heterogeneous environment has been presented.

The rest of this paper is structured as follows: Section II will introduce related work and demonstrate the need for new approaches. We will describe our approach in more detail in Section III. Section IV presents our new cognitive radio sensor protocol. In Section V we describe the demonstrator that was used for the evaluation. The results of our evaluation are shown in Section VI. The paper will conclude with a short summary and presents future work in Section VII.

II. RELATED WORK

Cognitive Radios are developed to find and utilize free frequency channels in a heterogeneous radio environment. Haykin [5] defines a Cognitive Radio (CR) as an intelligent wireless system that is aware of its surrounding radio environment. It changes its operating parameters according to the learning from the environment. Akyildiz et al. [3] describe the tasks which are required for an adaptive operation in an open radio environment, referred to as the cognitive cycle. Therefore, a Cognitive Radio has to follow three steps, Spectrum Sensing, Spectrum Analysis and Spectrum Decision. Spectrum Sensing monitors the actual occupancy of the spectrum. According to the monitored and analyzed results (Spectrum Analysis) the CR decides for a suitable dynamic spectrum access (Spectrum Decision). Akan et al. [4] describe the main design principles, potential advantages and application areas for Cognitive Radio Sensor Networks. It is shown that wireless sensor nodes equipped with cognitive radio can benefit from potential advantages of dynamic spectrum access. As already mentioned, one major task of a CR is to perform Spectrum Sensing. A detailed summary of spectrum sensing schemes is given by Yücek and Arslan [6]. Two important schemes - which are also utilized in our work - are energy detection and matched filter. Energy detection simply measures the energy transmitted by other wireless nodes over a corresponding frequency channel to detect if the channel is free or occupied. Matched filter analyzes the received data to check if a channel is occupied by a concurrent radio link with the same radio technology. Therefore, prior knowledge of concurrent radio links is required to demodulate and decode received signals. CRs deploy the Spectrum Decision over a common control channel according to the results of Spectrum Sensing and corresponding Spectrum Analysis.

Another important issue to be solved in our work is to guarantee certain Quality of Service (QoS) requirements by an appropriate MAC protocol. Chen et al. [7] propose an improved low-latency IEEE 802.15.4 MAC protocol. The improvement includes the modification of the superframe structure and the reduction of the MAC overhead. The contention access period is removed within the modified superframe. Therefore, the guaranteed time slots need to be pre-allocated to each of the participating devices. Additionally, the MAC layer data frame overhead is reduced. It only includes a payload of one byte and a frame checksum of two bytes. With these modifications the latency for 20 participating devices can be reduced from 17ms to 8ms. Another example for guaranteeing real-time services with IEEE 802.15.4 is presented by Yoo et al. in [8]. The approach proposes a modification of the guaranteed time slot allocation, but does not reach a real-time interval smaller than 10ms. Both schemes do not consider a heterogeneous radio environment and therefore can react on occurring interference.

The WirelessHART standard was developed by companies to meet the stringent requirements of control applications as presented by Song et al. in [9]. It adopts the IEEE 802.15.4 physical layer. On top of that it defines an own MAC. The MAC layer utilizes CSMA, TDMA and channel hopping to avoid interference with other concurrent radio links. Mesh topology with a network manager which configures the network, schedules and manages the communication between the nodes. Even though it avoids channels with interference it does not meet the requirements of real-time intervals smaller than 10ms.

Our approach follows the idea to avoid channels with interference or other concurrent IEEE 802.15.4 links. This idea, switching to another channel when an interference occurs, was also presented in one of our previous work in a different context in [10].

The control of a single inverted pendulum over an IEEE 802.15.4 wireless sensor and actuator network was presented by Hernandez et al. in [11]. The proposed approach provides only a sampling period of 32ms and also cannot deal with interference on the used frequency channel. The 3fold pendulum in our work needs control cycles less than 5ms. In [12] Yang et al., present the control of even two inverted pendulum, but for wireless communication an IEEE 802.11b radio link was used and also a heterogeneous radio environment was not considered.

III. Approach

To achieve firm real-time requirements in heterogeneous environments we make assumptions about the environment. First, there is free spectrum available, so called holes that change dynamically over time as we cannot solve the problem if there are no resources left. We further assume that the application data traffic is variable bit rate (VBR) where the system without the presence of interference is capable to fulfill the required real-time characteristics like data rate and delay with a certain margin left to tolerate some interference. Additionally we restrict the solution of this problem for single-hop scenarios in this work. Multi-hop scenarios need more complex solutions to provide the required QoS for firm real-time requirements. We plan to extend our approach to multi-hop capabilities in the future. To achieve this goal the system needs to be aware of the environment in the sense of Cognitive Radio Research.

We describe the idea with the help of a scenario where there are many sensor sources and a single data sink. The approach is not limited to this setup but for now this specific scenario helps to understand the design.

Channel Switching: In our approach sources and sinks agree on a channel usage sequence similar to a hopping sequence in frequency hopping. This happens before starting the system and can be dynamically adapted if needed. The predefined channel usage sequence improves the performance of the system as in the case of interference the nodes implicitly agree to hop to the next channel even if the interference does not allow to communicate on the actual channel. In contrast to other approaches previously published that are based on Cognitive Radio, we do not assume a dedicated reliable control channel for resource planning and cooperation.

The channel usage sequence can be extended in the future by blacklisting like Adaptive Frequency Hopping (AFH) does for Bluetooth. The advantage of blacklisting is that interferences of crowded channels can be omitted and the system has a better chance to achieve the QoS requirements of the application.

Detecting Interferences: To avoid ambiguity only one dedicated node in the network listens to the medium to detect interferences of other wireless technologies. This node is called Full Cognitive Node (FCN). Consequently, we name the other nodes Reduced Cognitive Nodes (RCN). If the measured interference of the FCN reaches a limit, this node sends a packet switch RF channel to all nodes. All reduced cognitive nodes in the network listen to these packets continuously and switch accordingly.

Additionally, all cognitive nodes switch channels if they receive a large packet that violates the predefined timing constraints of the application. The latter decision is helpful if other applications on nearby nodes start to send large packets. Optionally, the FCN can send an additional switch RF channel in this case too if delay constraints allow so.

Non-Invasive Behavior: Instead of starting to negotiate resource usage with the other applications we implement a non-invasive strategy by switching to another channel as fast as possible to keep the firm real-time constraints. We prefer this strategy as cooperation between wireless firm real-time applications is standardized only in optional sections of the specifications. Therefore, in real scenarios, we cannot assume that all wireless nodes in range are capable of this cooperation.

In the following, we summarize the approach starting from the detection to the switching rules. All nodes count, measure, analyze received data and apply a matched filter. The FCN additionally detects interference of other concurrent wireless transmissions by energy detection or more advanced schemes. Cognitive nodes switch to a new channel based on a predefined channel usage sequence in either two cases: (1) A large packet or (2) a switch RF channel packet is received. Thereby, we have defined a simple robust decentralized rule based system. We discuss some details of the implementation in the next section.

IV. Implementation Details

In this section, we provide more details of the protocol using flow charts and present the timing model to calculate the parameter settings.

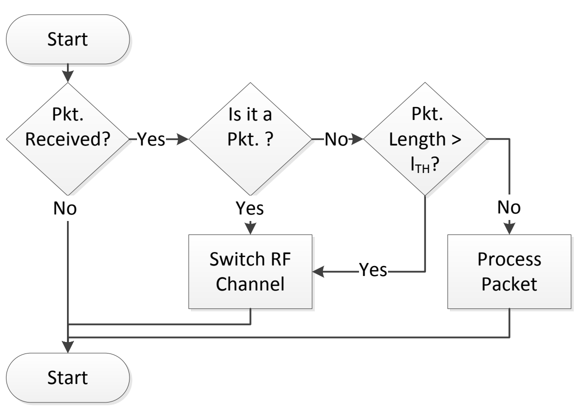

Fig. 1. Flow Diagram of Receiving Process Reduced Cognitive Node

The reduced cognitive node is kept very simple and does not have any timing conditions as can be seen in Figure 1. The only parameter needed for the protocol is the threshold length of a packet l_{TH} in bytes if a fixed data rate is used in the system or in packet duration if adaptive data rates like in IEEE 802.11 occur. In IEEE 802.11 depending on the signal to noise ratio and capabilities the transmission rate is between 1Mbps up to 11Mbps in IEEE 802.11b, but downwards compatible to original IEEE 802.11.

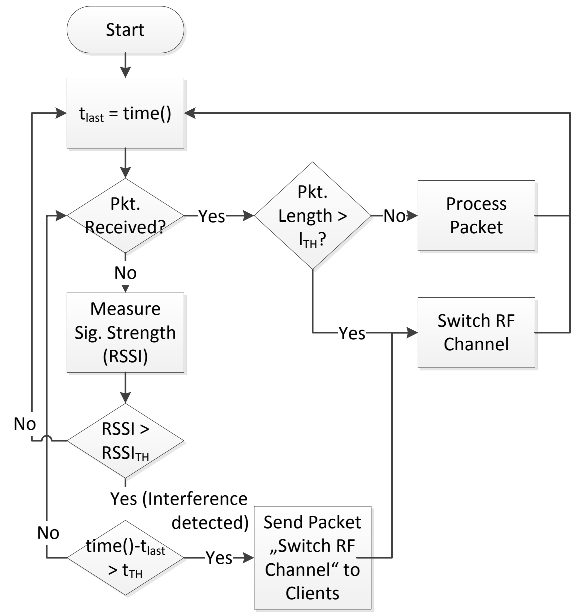

Fig. 2. Flow Diagram of Interference Mitigation Full Cognitive Node

For detection of the interfering signals we need access to the signals on the RF-Chip. We identified the following characteristics for concurrent transmissions and noise or other radio interference that can be measured with common RF-Chips.

- Interfering packets change the RSSI value of the receiver due to the preamble signal.
- Nearby transmitters result in high RSSI values.
- After the complete preamble the RF-Chip enters the state ”receiving”.

In contrast, noise or other radio interference results in the following characteristics.

- Interfering signals change the RSSI value of the receiver.
- Strong interference results in high RSSI values.
- Even with long periods of interference the RF-Chip does not enter the state ”receiving”.

Figure 3 illustrates the typical scenario where for a short time the FCN detects the violation of the critical RSSI threshold and starts a timer. When the interference stops before the timer expired, the FCN resets its timer again.

In Figure 4, the timer expires after the threshold t_{TH} so that the FCN decides to send a packet ”switch RF channel” to all nodes. If the RSSI is suitable to send, the FCN can send this packet successfully and all nodes change channels synchronously.

Figure 5 illustrates the case when interfering packets from other applications using the same channel occur. In Figure 5

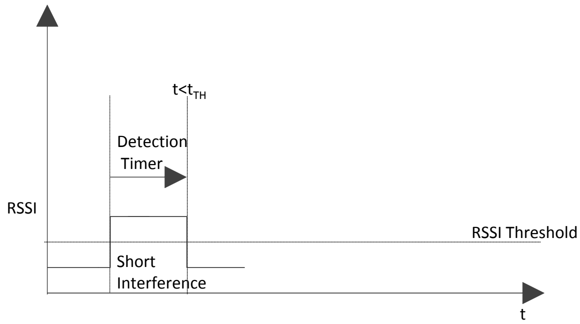

Fig. 3. Short Interference FCN

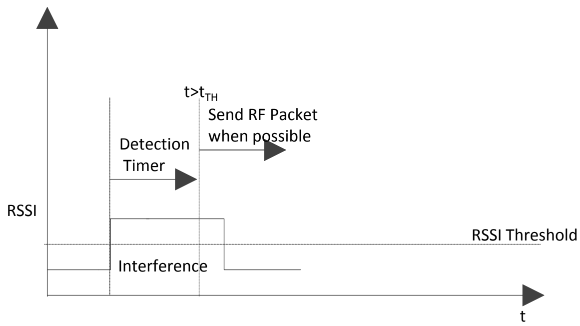

Fig. 4. Long Interference FCN

we see the case where a large packet is transmitted that violates the packet length threshold l_{TH}. All nodes will switch channels accordingly. The Reduced Cognitive Nodes will start to measure with the reception of the packet without the first part where the RSSI value hits the threshold. Table I summarizes the settings for our Protocol.

TABLE I
SETTING FOR NON-INVASIVE COGNITIVE RADIO

Parameter	Value	Description
$RSSI_{TH}$	$> CSMA_{TH}$	Threshold where Interference Detection Timer of FCN is started
t_{TH}	$> t_{maxDelay}$	Threshold when nodes switch channel due to long Interference
l_{TH}	$> t_{maxDelay}$	Threshold when nodes switch channel due to large packets

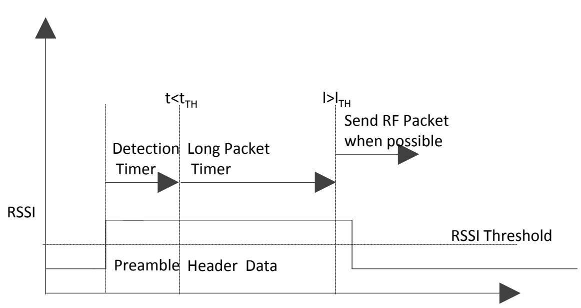

Fig. 5. Large Interfering Packet FCN

V. DEMONSTRATOR

The demonstrator for our new approach is a threefold pendulum which is controlled by a Matlab-driven Target-PC. The control loop of the system consists of sensors measuring angle values from all bearings of the pendulum. On a PC, a Matlab application calculates a control value, accordingly. Due to the weight and the handling of the cables it is not possible to mount wired sensors to each of the bearings. Therefore, wireless sensors with rotary encoders are mounted on each bearing. The wireless sensors in our systems are Reduced Cognitive Nodes as described in Section IV. A Full Cognitive Node collects the angle information from the RCNs and transfers it to the PC via serial interface. The setup of the demonstrator is depicted in Figure 6.

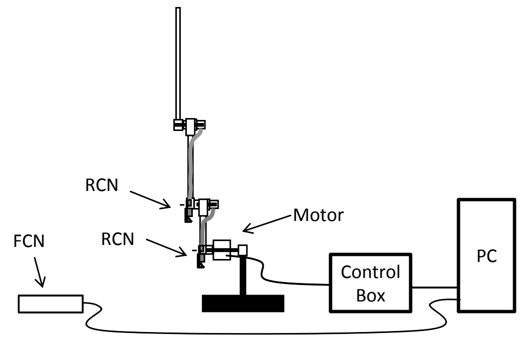

Fig. 6. Demonstrator - 3fold Pendulum

For real-time applications the packet size needs to be small to fulfill the timing constraints. The packet consists of 8 Bytes in five fields as illustrated in Figure 7.

Fig. 7. Packet Format

The PAN ID allows to distinguish own or interfering packets. The packet type can be *Registration Request*, *Registration Response* or *Data*. The source field specifies the originator of the packet and Data as well as CRC contain the obvious content.

As shown in Figure 8, each client working as a RCN starts to search for a FCN node. FCNs operate as a data sink transferring the data to the PC via serial interface. The RCN hops according to the channel usage sequence searching for a FCN that answers its request. In the reply the FCN returns also the timing conditions and could add further optional settings like a new channel usage sequence. Register Reply packets need to be considered also by already connected nodes as timing conditions like maximum waiting time might change during runtime in our setup. The RCN nodes send their data in a round robin fashion in a non-invasive manner by waiting according to the settings of the FCN in the reply packet as illustrated in Figure 9.

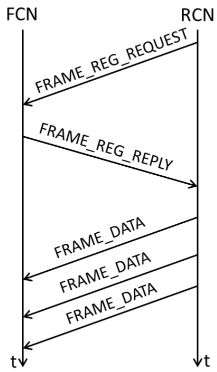

Fig. 8. Protocol

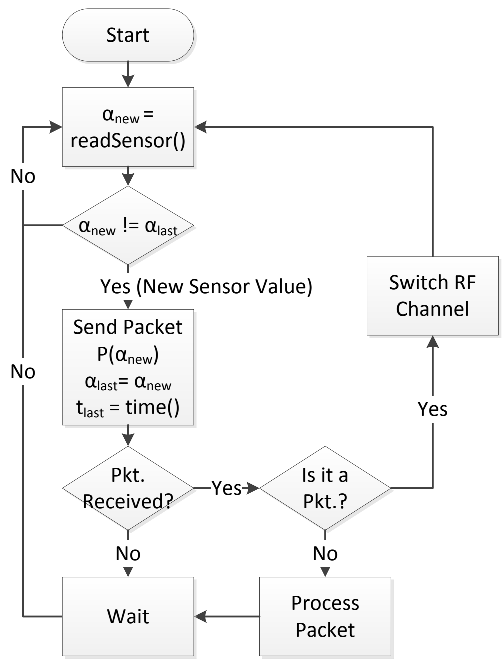

Fig. 9. Complete Flow Diagram of Reduced Cognitive Node

VI. Evaluation

The demonstrator introduced in Section V serves for evaluation of the cognitive radio sensor protocol. It is a very intuitive measurement tool for proofing the keeping of the firm real-time requirements as the violations of the requested max-delay of 5 ms can be noticed by strong control movements of the system. For the evaluation setup an additional interfering wireless sensor was introduced to the radio environment as well as a WLAN IEEE 802.11g access point. The corresponding network topology is shown in Figure 10.

To demonstrate the effect of a concurrent transmitter, the transmitted and captured angle information were displayed in Figure 11 to Figure 13. In Figure 11, both angle values, transmitted by two RCNs and received by the FCN, are displayed in the time interval of 5s. During this reference measurement we switched off all interferences.

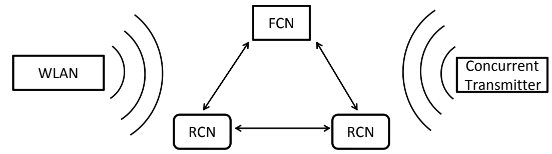

Fig. 10. Radio Environment for Evaluation

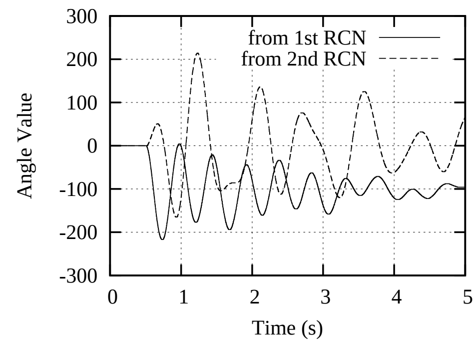

Fig. 11. Complete Measurement Cycle for two Sensors as RCNs

In the next setup, an interfering wireless sensor transmits short packets with 40Bytes every 5ms. The length of packets is shorter than the defined threshold of 50Bytes according to the timing constraints The transmission of 50Bytes with 250kbps bit rate lasts for 50*8b/250kbps resulting in approx. 2ms which is less than the maximum delay of 5ms. The transmission of the nodes themselves also lasts for approx. 1ms including internal processing and RF Chip processing. Therefore, these disruptions can be tolerated by the pendulum and consequently no channel switching is necessary. The influence on the measured angle values can be seen in Figure 12.

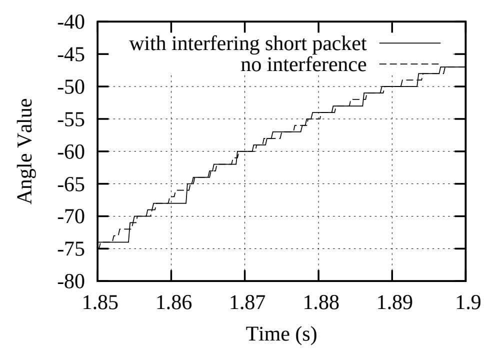

Fig. 12. Received Angle Values from one RCN with and without interfering IEEE 802.15.4 Packets of Size 40Byte

The displayed angle values show two evaluation runs, without interference (dashed line) and with interfering packets with length of 40Byte (solid line). In Figure 12, each 5ms a short distortion of the captured angle values occurs. Due to the fact that these short interfering packets can be tolerated no channels switching was invoked as predicted. This is why we see these effects occur consecutively.

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In the last setup, a concurrent wireless sensor transmits packets of size 70Byte which is above the defined threshold. The resulting angle values are depicted in Figure 13.

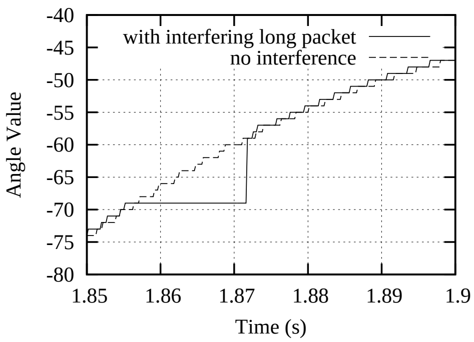

Fig. 13. Received Angle Values from one RCN with and without interfering IEEE 802.15.4 Packets of Size 70Byte

At 1.855s, the concurrent wireless sensor transmits a packet of 70Bytes which causes a distortion of the captured angle value and a corresponding channel switch. After all nodes have switched to the next channel, values are smooth again at time 1.872 and no consecutive distortions of the angle value occur. If the nodes switch to a channel where WLAN is transmitting, measurements show the same behavior as it shows with large interfering packets. After switching to a new channel the values are smooth again.

Figure 14 shows the frequency spectrum in a waterfall plot to illustrate the switching to the next channel.

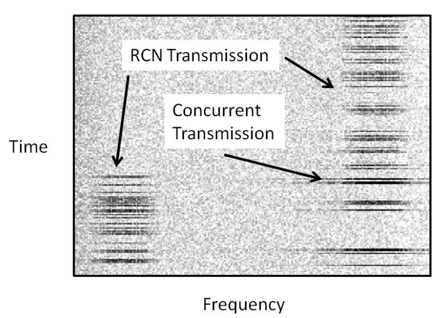

Fig. 14. Switching to the next Channel due to interfering large packets

The top of the plot displays the past whereas the bottom displays the most recent measurements. In the beginning, only the RCNs are transmitting their angle information. As soon as the concurrent wireless sensor starts its transmission, all RCNs and FCN switch to the next channel and proceed with the transmission of the angle information.

The presented evaluation results demonstrate the correct functionality of the system and illustrate the cognitive capabilities of the sensor application.

VII. Conclusion and Future Work

In this paper, we presented a new non-invasive cognitive radio protocol for a sensor application with firm real-time requirements. Our decentralized rule based approach works beyond existing reservation and synchronous Time Division Multiple Access (TDMA) schemes. We demonstrated that we provide solutions in a heterogonous radio environment by a firm real-time demonstrator based on 802.15.4 Our approach detects own data packets, concurrent transmissions using same wireless technology AND other interfering wireless technologies. Finally, we present the control of a pendulum with delay requirements less than 5ms to evaluate and prove the effectiveness of the approach.

For the future, we will complete the protocol with blacklisting of crowded channels and security mechanisms that avoid the risk that unauthorized nodes send packets ”switch RF channel”. Furthermore we will work on multi-hop capabilities.

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References

[1] C. F. Garcia-Hernandez, P. H. Ibargüengoytia-Gonzalez, J. Garcia-Hernandez, and J. A. Perez-Diaz, “Wireless sensor networks and applications: a survey,” *International Journal of Computer Science and Network Security*, vol. 17, no. 3, pp. 264 –273, 2007, survey.

[2] P. A. Laplante, *Real-time systems design and analysis - an engineer's handbook (3. ed.)*. IEEE, 2004.

[3] I. Akyildiz, W. Y. Lee, and K. Chowdhury, “Crahns: Cognitive radio ad hoc networks,” *Ad Hoc Networks (Elsevier) Journal*, vol. 7, no. 5, pp. ’810–836’, Jul. 2009.

[4] O. B. Akan, O. B. Karli, and O. Ergul, “Cognitive radio sensor networks,” *Netwrk. Mag. of Global Internetwkg.*, vol. 23, no. 4, pp. 34–40, Jul. 2009.

[5] S. Haykin, “Cognitive radio: brain-empowered wireless communications,” *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 2, pp. ’201–220’, Feb. 2005.

[6] T. Yücek and H. Arslan, “A survey of spectrum sensing algorithms for cognitive radio applications,” *IEEE Communications Survey & Tutorials*, vol. 11, no. 1, pp. 116–130, 2009.

[7] F. Chen, T. Talanis, R. German, and F. Dressler, “Real-time Enabled IEEE 802.15.4 Sensor Networks in Industrial Automation,” in *IEEE Symposium on Industrial Embedded Systems (SIES 2009)*. Lausanne, Switzerland: IEEE, July 2009, pp. 136–139.

[8] S. eun Yoo, P. K. Chong, D. Kim, Y. Doh, M.-L. Pham, E. Choi, and J. Huh, “Guaranteeing Real-Time Services for Industrial Wireless Sensor Networks With IEEE 802.15.4,” vol. 57, no. 11, pp. 3868–3876, November 2010.

[9] J. Song, S. Han, A. Mok, D. Chen, M. Lucas, M. Nixon, and W. Pratt, “WirelessHART: Applying Wireless Technology in Real-Time Industrial Process Control,” in *IEEE Real-Time and Embedded Technology and Applications Symposium (RTAS 2008)*. St.Louis, USA: IEEE, 2008, pp. 377–386.

[10] T. Esemann and H. Hellbrück, “Non-invasive cognition driven spectrum access in medical application via baseband processing,” in *Proceedings of the 7th Karlsruhe Workshop on Software Radios*, Karlsruhe, Germany, Mar. 2012.

[11] A. Hernandez, J. Faria, J. Araujo, P. Park, H. Sandberg, and K. H. Johansson, “Inverted Pendulum Control over an IEEE 802.15.4 Wireless Sensor and Actuator Network,” in *Proceedings of the European Wireless Sensor Networks (EWSN)*, Bonn, 2011.

[12] A. Yang, G. Irwin, W. Naeem, and K. Li, “Application of wireless network control to a two inverted pendulum system,” in *Proceedings of the 22nd IET Irish Signals and Systems Conference*, Dublin, 2011.