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# Adaptive Channel Map for Time Slotted Channel Hopping Industrial Wireless Networks ⋆

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**Abstract:**
The use of wireless networks in industrial environments is a reality today because of its advantages, but with the use of such networks, the problem of coexistence becomes inevitable. This paper presents a system to deal with the problems brought on by the networks coexistence, and thus avoid a reduction in the robustness of the network in which this issue has been accomplished. An adaptive channel mapping system is proposed in industrial wireless networks, where the affected channels are removed from the channel map used. A case study of the adaptive channel mapping system in a *Wireless*HART network is performed.

*Keywords:* Industrial automation, industrial wireless networks, coexistence, channel map.

## 1. INTRODUCTION

The Industrial Wireless Networks (IWN) reached high application over the years, due to its main characteristics such as reduced infrastructure, ease of installation and maintenance, besides the impetus generated by the industry 4.0, see Sha et al. (2017). Among the existing wireless industrial communication protocols, the most commonly used are *Wireless*HART (WH), ISA100.11a and WIA-PA, see Wang and Jiang (2016). However, wireless industrial communication networks present undesirable characteristics, as the latency of communications, energy limitations and physical layer failures, see Künzel et al. (2018).

Another problem that arises with the use of wireless networks is the coexistence. When employing this kind of network in industrial environments applications, coexistence usually occurs, because of the presence of different networks that share the same frequency spectrum, such as networks based on the IEEE 802.15.4 standard, like WH, and IEEE 802.11 (WiFi), see Ben Yaala et al. (2016). These networks share the industrial, scientific and medical (ISM) frequency band, see Winter et al. (2014). There are techniques that can jointly minimize the problems generated by the networks coexistence, of which we can mention Time Slotted Channel Hopping (TSCH), Direct Sequence Spread Spectrum (DSSS), Time Division Multiple Access (TDMA) and also blacklisting, see HART Communication Foundation (2009). Commonly IWN natively use TDMA, DSSS and TSCH. TSCH is a channel access method with the objective of guaranteeing the diversity of spectrum use, where on each communication is calculated a new channel to be used. The choice of the active channel at any given moment is dependent on the instant of time the network is in, the channel offset of the link to be used and the channel map. Blacklisting techniques are a possible improvement and this work will explore them and present an adaptive channel mapping system.

Channel mapping can be divided according to some characteristics, among them the most common ones are: static/dynamic mapping and centralized/distributed mapping. The mapping presented in this work is dynamic, that is, it varies with time, and centralized, where only one channel map is used in all network devices. Some advantages of this dynamic and centralized approach are dynamic interference aware and low complexity, hence low computational cost. In industrial environments, it is possible that there are both permanent interferences, as well as intermittent interference, and in these situations, the use of a static channel map will not be appropriated.

For adaptive channel mapping application, it is necessary to observe in which channels interferences are present. This can be done directly, through the channels Energy Detection (ED) when the network is not in use, or indirectly, measuring the transmission failures for each channel individually, and thus infer that the channels with the highest loss rate are the channels most affected by interference.

In this work, the spectrum sensing is done by the ED achieved in a distributed and collaborative way. The selection of the worst channel is realized by the $k$-worst algorithm, and the updating of the channel map in all the network devices is done using the command designed for this function. As presented, this paper shows a full adaptive channel mapping system, from environment analysis to channel map updating, aiming to change the channel

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map to ensure that communications do not occur on channels that are affected by coexistence.

As a case study for this work, the WH protocol will be used. The laboratory where this work is being developed has all the necessary tools for the analysis of this protocol including a Network Manager (NM), Network Access Point (NAP), and Field Devices (FDs).

This paper is divided as follows: Section 2 presents some related works. The proposed approach and test methodology are presented in Section 3. Section 4 describes the results. Section 5 present the conclusions and future works.

## 2. RELATED WORKS

In Watteyne et al. (2009) the authors present a study that relates the reliability of an IWN with the diversity of frequencies used, in order to describe the importance of the use of channel hopping in such networks. Two main contributions are presented. The first is the comparison made between a network operating using only one channel, in relation to a network that uses channel hopping. Using multiple channels, significant improvements in network efficiency and stability are observed. The second major contribution of this work is in tests that measure the relationship between channel selection and increased network performance.

In Winter and Pereira (2014) the authors present a method for spectrum sensing in a WH network. As a form of spectrum sensing, the ED technique is used. It requires low computational and implementation resources. One of the great advantages of this sensing strategy is its computationally feasibility in real time, allowing a fast diagnosis of the spectrum without interfering or changing the communications integrity of the WH network. A change is made to the typical TDMA state machine to include a state for spectrum sensing. This method has the advantage of being distributed and cooperative, that is, all the devices present in the network realize the spectral sensing, on the other hand an issue is observed, because when performing the channel mapping, the removed channels will no longer be parsed, and in case of a temporary interference, it will not be detected when this interference no longer exists.

In Gunatilaka et al. (2017) the authors also present the channel mapping impacts in a IWN. The impacts of channel mapping on network topology, routing and network performance in real time are analyzed. The authors cite three main contributions of the paper. The first one is the empirical study that concludes that the performance of a WH network does not increase monotonically with the increasing number of channels used. The second major contribution is the proposal of a channel and link selection algorithm performed during the deployment of the network, or during its maintenance. This algorithm performs automated channel selection as a way to balance channel and route diversity. Finally, the selection algorithms are evaluated in a WH test network, where the experimental results demonstrate the significant increase of the network capacity to meet the routing and scheduling demands of the flows. As a selection metric, Packet Reception Ratio (PRR) is used to estimate link reliability, where PRR is defined as the ratio between packets transmitted and packets successfully received. In order to identify the best channels, a brute force algorithm was used to identify which set of channels offers the maximum number of available links, and for this a 80% PRR threshold was used. In this work it is not clear how the channel map update is performed on the devices present in the network. End-to-end Packet Delivery Ratio (PDR) is used as the metric to quantify network reliability.

In Zorbas et al. (2018) the authors discuss the use of local or global channel map in networks using the IEEE 802.15.4 TSCH standard. First is a theoretical study that presents the significant increase of packet delay when using local channel mapping technique, in a situation where many channels are added to the blacklist, and different channel offsets are used. Following is a method of global channel mapping to overcome the problems described above in the case of local mapping. Finally, a performance analysis is performed through IEEE 802.11 network coexistence tests, as proof that the proposed global blacklist reduces the delay and increases the PDR. To confirm the theoretical concepts presented in the work, tests are performed in a simulation environment, where radios are placed in random positions, where each one transmits a packet per slotframe. IEEE 802.11 access points are also used as interference generators. Monitoring of the number of delayed packets is performed as a network performance metric, and then evaluating the efficiency of the selection algorithms.

In Kotsiou et al. (2019) the authors present different techniques for channel mapping, distributed and centralized. Dependency analysis of these techniques with the scheduling algorithms are performed. Experimental tests are presented to validate the relevance of the use of channel hopping, tests performed in the form of simulation. Performance testing is conducted by focusing on the smart building environment using an open-source Software Defined Network (SDN) implementation. The metrics for comparing results are the link-level PDR, as well as the percentage of collisions. Open questions regarding channel mapping are presented, such as the presence of coexistence between TSCH networks and also the issue of reducing channel diversity by adding many channels to the blacklist. The work is concerned with presenting the taxonomy and main components necessary for the development of a channel mapping system.

Regarding channel sensing in order to characterize the quality of each channel, a widely used technique is to measure the PDR per channel, Kotsiou et al. (2019). The technique seems like a good idea, but there is a problem not apparent for the case of adaptive channel mapping. This feature can be extracted for all channels when the channel map used in communications is complete. Assuming the removal of some channels from the allowed channel list, it will not be possible to extract the packet loss rate for these channels as they are no longer being used in communications.

Another known technique for avoiding busy channel transmissions is the use of Clear Channel Assessment (CCA), see Tytgat et al. (2012). This technique is very effective, but in the case of long-term interference it has a certain weakness. Assuming the existence of constant coexistence in some channels used in the network, whenever some communication is going to use any of these channels, the transmission will be aborted, so that in a next slot it can be realized in some other channel. It is observed that this way the average delay of the packets will increase, because some transmissions will not be made after the CCA gets a negative result. However, this may be the best choice for cases with interference that is dynamic in relation to both existence and frequency of occurrence.

Many of the channel mapping works has little concern with how channel selection is performed, most works using the $k$-worst selection method. This method performs channel analysis through a given metric, and the lowest performing $k$ channels are removed. Regarding complexity, this is a great technique as it is quite simple, but this technique is not adaptable to the number of channels removed, and this can be detrimental in many cases.

This work differs from the others by presenting a complete adaptive channel mapping system, from spectrum sensing to channel selection to the application of the new channel map on wireless network devices.

## 3. METHODOLOGY

In this section it will be presented the method developed to perform the analysis of the channels, and subsequent blacklist modification. The complete process can be divided into three main stages: Spectrum sensing; Channel map creation; Channel map update. These steps are performed periodically, thus ensuring the proposed adaptive characteristic, where it is possible to adapt to existing coexistence.

The sequence diagram representing a channel map update cycle is shown in Fig. 1. It is important to emphasize that in this diagram only one FD is represented, but the same sequence is valid for multiple FDs. The following subsections present in more detail the stages of adaptive channel mapping system proposed in this work.

### *3.1 Spectrum Sensing*

The first stage of the process refers to the sensing of the frequency spectrum. At this stage the objective is to obtain information about the health of each channel used. In this work, it is intended to perform the sensing in a distributed way, that is, all the network devices will perform the sensing. The channel analysis will be done in a direct way, where the ED in a given channel will be performed, when there is no traffic in the network.

The spectral sensing method proposed by Winter and Pereira (2014) was used. This method uses timeslots with transmission links that will not be used at the moment to perform the ED. The analyzed channel must be present in the channel map used in the network, as it is the same one used in communications. This analysis is only useful when the channel map is complete, i.e. no channels added to the prohibited channel list. As this work deals with adaptive channel mapping, the direct application of this form of energy detection is not adequate.

As a way to adapt this solution to the proposed channel mapping work, a modification of the spectrum sensing

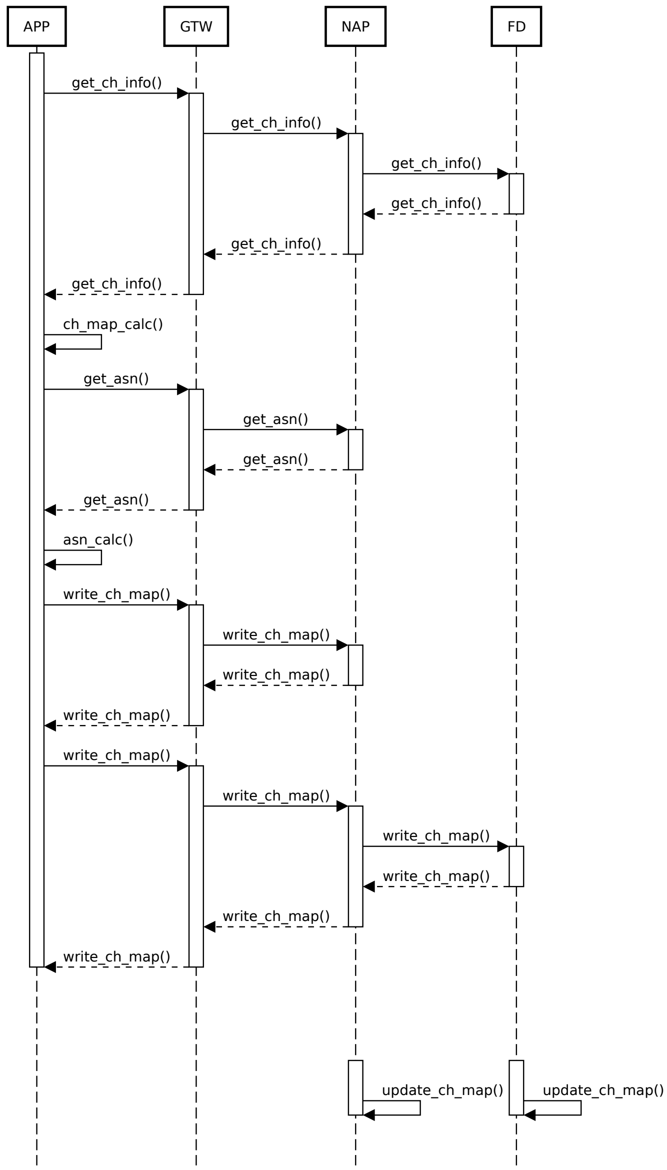


Fig. 1. Sequence diagram.

state was performed. In this work, channel sensing always use the full channel map. Therefore, in a certain transmission slot, if communication with another network device is performed, the "normal" channel map is used, if there is no need for transmission the device goes into spectrum sensing state and the complete channel map is used. This modification is fundamental for the adaptive channel mapping proposed in this work. Assuming the removal of a specific channel from the map due to its occupation and after some time the channel becomes free again, the system should be able to analyze the channel and reuse it. Subsequently, through the information obtained in the first stage, the selection of channels will be done properly.

### *3.2 Channel Map Creation*

The blacklist channel selection can be done in different ways, the most common way is to use the $k$-worst technique, where the fixed number of worst channels will be removed, see Kotsiou et al. (2019). The main advantages of the $k$-worst method are ease of implementation and fast execution, but it has weaknesses in relation to the number of removed channels. If the number of affected channels is greater than $k$, some affected channels will not be removed from the map. In case the number of affected channels is less than $k$, unaffected channels will be removed from the list.

This paper focuses more on the adaptive channel mapping system as a whole and its application to the WH protocol. Greater attention is applied to the channel map sensing and updating steps.

### *3.3 Channel Map Update*

The last step to update the channel map in all devices present in the network. It is noted that in this step it is important that all devices have the updated channel map simultaneously so that there are no communications failures between devices with different channel maps.

To execute the channel map update in all the devices simultaneously, the Absolute Slot Number (ASN) is used. ASN is a timestamp present in each of the slots in a TDMA network, and is not repeated in different slotframe cycles. When sending the update channel map command to the devices, two parameters are used, the first one is the channel map, and the second is the ASN in which this command should be run on the device, as observed in the Fig. 2. After receiving the command, a timer is triggered on the device, and when the ASN value is reached, a callback is performed, responsible for executing the channel map update command. At this moment all devices present in the network will be updated, thus not falling into the problem presented previously, where neighboring devices have different channel maps. To calculate the ASN that should be passed as parameter, the current ASN is observed, and then the number of slots is added proportionally to the time until the execution of the command.

| 0 | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Channel Map | | ASN | | | | |

Fig. 2. Write Channel Map Command

In the sequence diagram presented in Fig. 1 it can be seen that the channel map write commands (*write_ch_map*) are executed in NAP and FD in different times, but the channel map update command (*update_ch_map*) is performed simultaneously on both network devices.

### *3.4 Practical Operation*

When starting the network, the first device provisioned is the NAP, which is connected directly to the gateway. During this first moment, the written channel map is complete, that is, it contains all channels available for use. For WH, 15 channels are released.

With the adaptive mapping system activated, every time a predefined period is reached, spectrum sensing data stored in each of the FDs present in the network are read. After that, this data is used by the algorithm responsible for defining the new channel map to use. Finally, the new channel map is written to each of the network devices.

As already presented in Section 1, the tests will be performed in a WH network setup, which will be shown in more detail in subsection 3.5. In order to perform the algorithm, small changes were made in the protocol. The WH protocol only allows the update channel map in the gateway, and requires the network restart for application on all devices. The modification performed causes all devices to have the ability to receive channel map update command. The default write channel map command perform instant execution, that is, when receiving the command, the device performs the channel map change, and the modified command allows sending the ASN which the channel map will be updated, making possible that channel map refresh over the entire network occurs at the same time, and communication conflicts between devices with different channel maps are not generated.

### *3.5 Experimental Setup*

As previously mentioned, the case study will be conducted using a WH network. In a Linux PC, the NM, Gateway and NAP-Host applications are executed, developed in the research laboratory, and responsible for creating and maintaining the network. In this same computer it is also present the application responsible for the adaptive channel mapping. The general infrastructure is presented in Fig. 3. The hardware used in NAP and FD functions is the same, developed in Muller et al. (2011). Different firmwares are developed for these different functions.

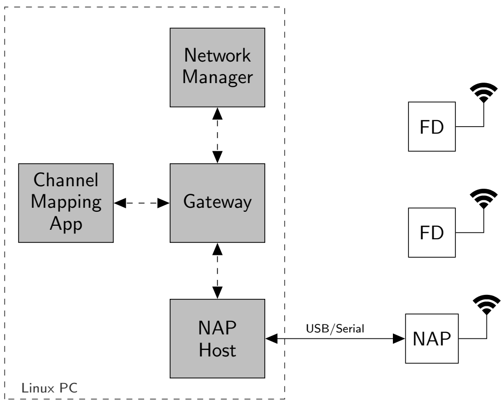


Fig. 3. Experimental setup.

### *3.6 Test Methodology*

As a way to analyze the performance of the proposed algorithm, tests were performed in a WH network with the experimental setup presented in subsection 3.5. FDs were configured with burst interval of 1 second, i.e., every 1 second the device sends its process variable to NAP.

The test purpose is to verify the operation of the proposed channel mapping system, for this the test is performed in two steps, both with coexistence.

(1) Adaptive channel mapping system disabled;
(2) Adaptive channel mapping system enabled.

The performance metric was the transmission failure ratio. In each period the number of packets transmitted by FDs to NAP and the number of failed transmissions (missed ACKs) are measured. Transmission failure ratio is provided in (1).

$$\text{Transmission Failure Ratio} = \frac{\text{Failed Transmissions}}{\text{Packets Transmitted}} \quad (1)$$

In order to verify the system performance in a coexisting environment, interference was applied using a WiFi network (IEEE 802.11). The LinkIt Smart 7688 Duo development board was used, Studio (2019). The LinkIt Smart 7688 Duo is a development board based on an OpenWrt Linux distribution and features the MediaTek MT7688 as its main processor. Due to the use of the Linux OpenWrt operating system, it is possible to automate tasks on the access point, such as setting WiFi network parameters, thus allowing greater control over the generated coexistence. The setup used in the coexistence test is shown in Fig. 4.

As a stress test, continuous traffic was generated on the WiFi network using the *iPerf3* application. In test case performed in this work, *iPerf3* was run in server mode on the WiFi access point, and in client mode on the computer connected to it. For the test performed the access point was configured with IEEE 802.11b and the use of channel 6 of the WiFi network was fixed. As observed in Fig. 5, the channel used generates coexistence with channels 16, 17, 18 and 19 in IEEE 802.15.4 network. This occurs because each channel on the IEEE 802.15.4 protocol has a bandwidth of 2 MHz, and the spacing between adjacent channels is 5 MHz. On the other hand, in 802.11b protocol, the bandwidth of each channel is 22 MHz.

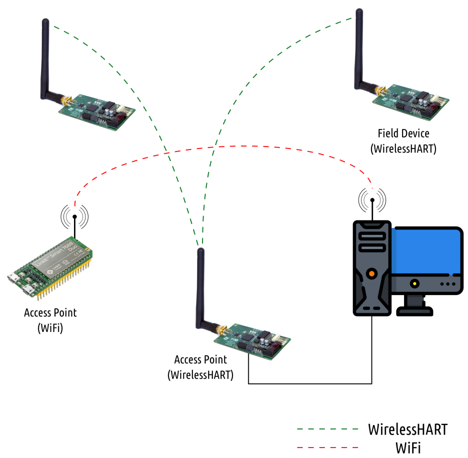


Fig. 4. Coexistence setup.

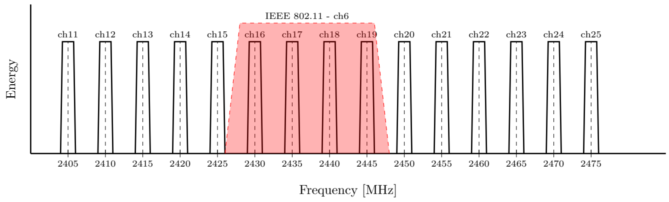


Fig. 5. Coexistence between IEEE 802.15.4 (WH) and IEEE 802.11b (ch6).

## 4. RESULTS AND DISCUSSION

After the coexistence experiment is performed, with and without the use of the channel mapping system, the results are presented in Fig. 6. In this test channel selection was used with the $k$-worst method, with $k$=4. The first half of the graph shows the ratio without using the adaptive mapping system, while in the second half the mapping system is enabled. There is a reduction in the failure ratio with the use of channel mapping system. The data presented was analysed statistically.

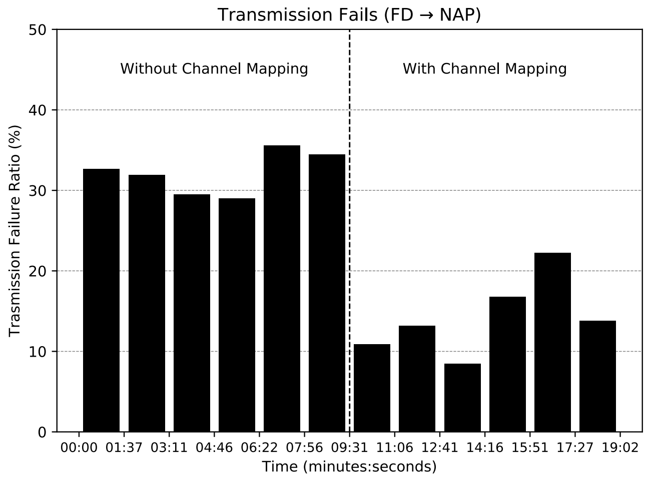


Fig. 6. Transmission fails.

In order to ensure that the adaptive mapping system has a direct influence on the transmission failure ratio, an analysis of variance (ANOVA) is performed using a confidence level of 95% ($\alpha = 0.05$). Table 1 summarizes the results obtained by performing ANOVA.

Table 1. ANOVA results.

| Source of Variation | Degrees of Freedom | Sum of Squares | Mean Square | $F_{calc}$ | $F_{tab}$ |
|---|---|---|---|---|---|
| Channel Map | 1 | 0.0967 | 0.0967 | 64.35 | 4.96 |
| Error | 10 | 0.0150 | 0.0015 | - | - |
| Total | 11 | 0.1117 | - | - | - |

As F-Value$_{calc}$ is greater than the F-Value$_{tab}$ it is possible to conclude that the technique significantly affects the transmission failure ratio. The average and standard deviation with and without using the adaptive channel mapping system are presented in table 2.

Table 2. Failure ratio statistics.

| Channel Mapping System | Average | StdDev |
|---|---|---|
| Disabled | 0.3218 | 0.0239 |
| Enabled | 0.1423 | 0.0439 |

After applying adaptive channel mapping, the transmission failure ratio fell on average 17.95%. It is observed that the use of adaptive channel mapping is not the definitive solution to solve the problems brought about by coexistence, and therefore its use is proposed along with other techniques such as CCA and DSSS. This system should be treated as one more layer to increase the robustness of an IWN.

## 5. CONCLUSION

This work was motivated by one of the main weaknesses observed in the use of IWN, coexistence, which consequently leads to a reduction in the robustness of the network. The main contribution is the presentation of a full adaptive channel mapping system, consisting of spectrum sensing, channel map creation and channel map updating steps. The main objective is to reduce the problems brought by coexistence, thereby ensuring greater network robustness, and efficient energy consumption. For spectrum sensing the energy detection method is used, the $k$-worst algorithm is the choice for channel map creation, and a personalized channel map update command is presented.

Tests were performed in an environment under coexistence with IEEE 802.11 network where measurements were taken of the number of transmitted packets and also the number of transmission failures, where the FDs did not receive ACK from the transmitted packets. Statistical analyzes performed after the execution of the experiment show the effectiveness of the proposed system.

As future work, new channel selection techniques will be developed where statistical concepts are used and the channels will be removed only if they have a significantly higher detected energy than the others. Case studies with variable coexistence as a way to verify the efficiency of the proposed system for dynamic interference are also required.

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