Adaptive Beacon Transmission in Cognitive-OFDM-Based Industrial Wireless Networks

Lian Li, Cailian Chen, Yiyin Wang, Tian He, and Xinping Guan

***Abstract*— Wireless interferences from heterogeneous networks in the crowded industrial scientific medical band set up technical barriers for reliable communication of industrial wireless network (IWN). In this letter, an adaptive beacon transmission strategy is proposed for dynamically scheduling the cognitive-OFDM IWN to avoid channel interferences without using a dedicated control channel. Preambles of beacons are specifically designed in the PHY layer to embed specific information. A generalized likelihood ratio test (GLRT)-based approach is applied to detect the beacon transmission and a maximum likelihood estimator is employed to estimate the beacon information embedded in the preamble. The performance of the GLRT approach to detect the adaptive beacon transmission is evaluated through simulations and practical experiments. The detection and decoding accuracies of the proposed adaptive beacon transmission are close to 100% with reasonable signal-to-noise ratio even under interference.**

***Index Terms*— Beacon, ISM band, interference, IWN.**

I. Introduction

INDUSTRIAL wireless networks (IWNs) have been regarded as an attractive communication option for industrial automation systems because of their low cost, flexible configuration and easy deployment. IWNs are usually deployed in the Industrial Scientific Medical (ISM) band. However, numerous wireless applications (WiFi, ZigBee et al.) use this band for communication, which may result in narrowband interference (NBI) and wideband interference (WBI) to IWNs [1]. Hence, it is very challenging to guarantee reliable communication for IWNs in the crowded ISM band.

Industrial wireless standard WirelessHART [2] has been released for industrial wireless communications with channel blacklist and predefined channel hopping strategies to circumvent static interferences. However, it cannot adapt to dynamic and quickly changing interfered environments since the network neither adjusts the spectrum allocation timely nor senses the environments frequently. There is usually a dedicated control channel to transmit control messages if the the network dynamically changes its communication policy. However, it is very challenging and difficult to establish and maintain a common control channel under dynamic spectrum environments [3], especially in the unlicensed ISM band [1]. Related works using a channel hopping strategy to establish the control channel are also surveyed in [3]. Nevertheless, the communication efficiency is less attractive and the reliability may be influenced by WBI. Without using a control channel, lightweight coordination strategies are designed in [4] and [5] to reliably deliver coordination information between heterogeneous networks. However, the transmission reliability cannot be guaranteed under interference.

In this letter, without using a dedicated control channel, we propose an adaptive beacon transmission strategy for dynamically scheduling the IWN to avoid channel interferences. Cognitive orthogonal frequency division multiplexing (Cognitive-OFDM) technique is adopted in the physical layer of the IWN because of its flexibility on resource allocation and superiority on interference avoidance in the crowded ISM band [1]. In the Cognitive-OFDM IWN, two different beacons are adaptively transmitted by the access point (AP) for sharing different information with field nodes (FNs) under different interference situations. The preambles of beacons are specifically designed in the PHY layer to embed the information. A generalized likelihood ratio test (GLRT) based approach is proposed to detect the beacon transmission and a maximum likelihood estimation (MLE) based method is employed to estimate the beacon information embedded in the preamble. The proposed adaptive beacon transmission is evaluated and its effectiveness is demonstrated through simulations and experiments. A traditional fixed beacon transmission strategy is also evaluated, which is ineffective under interference. However, the detection and decoding accuracies of the proposed adaptive beacon transmission are close to 100% with reasonable SNR even under high power interference.

II. System Overview

The proposing Cognitive-OFDM IWN is a star network and consists of one AP and many FNs. The AP chooses one available channel from C discontinuous channels in initialization. As shown in Fig. 1, the bandwidth of each channel is B, each channel has N subcarriers, and all subcarriers are divided into Q subbands. A resource block is one subband with a timeslot, and it can be allocated to a FN to transmit a packet. The AP conducts interference detection at the beginning of each scheduling period to identify idle subbands, then two different beacons are adaptively transmitted by the AP for sharing different information according to different interference situations. One is the control beacon to deliver the allocation information of resource blocks using a single idle subband under NBI (see the first two periods in Fig. 1). After receiving the control beacon, the FNs begin data transmission according

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L. Li, C. Chen, Y. Wang, and X. Guan are with the Key Laboratory of System Control and Information Processing, Ministry of Education of China, Department of Automation, Shanghai Jiao Tong University, Shanghai 200240, China (e-mail: li_li_an@sjtu.edu.cn; cailianchen@sjtu.edu.cn; yiyinwang@sjtu.edu.cn; xpguan@sjtu.edu.cn).

T. He is with the Key Laboratory of System Control and Information Processing, Ministry of Education of China, Department of Automation, Shanghai Jiao Tong University, Shanghai 200240, China, and also with the Department of Computer Science and Engineering, University of Minnesota, Minneapolis, MN 55455 USA (e-mail: tianhe@cs.umn.edu).

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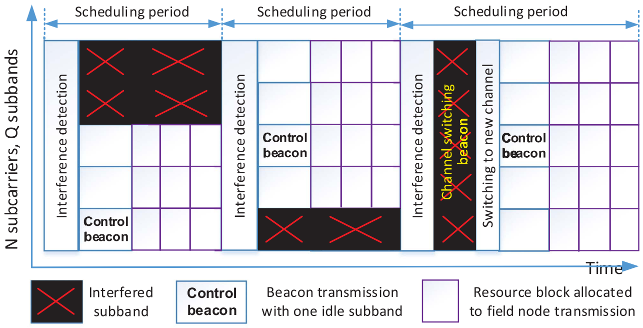

Fig. 1. Scheduling period of the Cognitive-OFDM IWN.

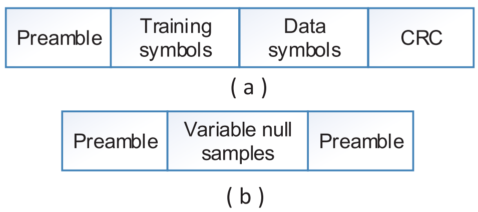

Fig. 2. (a) Structure of the control beacon, (b) Structure of the channel switching beacon.

to the resource blocks allocation information. The other is the channel switching beacon to deliver channel switching information using all subbands under WBI (see the third period in Fig. 1). The channel switching beacon leverages the distance between two repeated preambles to convey the targeted switching channel information, which is a more reliable strategy under WBI. After receiving the channel switching beacon, all devices switch to a new idle channel, which is selected by the AP through interference detection from the rest $C-1$ channels, then a new control beacon will be transmitted by the AP for allocating resource blocks in the new channel.

III. Beacon Design and Detection

In this section, we present the design and detection of the control beacon and channel switching beacon, respectively.

A. Preamble Design for Control Beacon

When there is no interference or only NBI, the AP chooses to transmit a control beacon using a single idle subband to allocate the resource blocks of the remaining scheduling period to FNs. To embed the used subband information, we design different preambles for different subband utilization. The preamble is an OFDM symbol, which is a Zadoff-Chu (ZC) sequence transmitted in the chosen subband. As shown in Fig. 2 (a), training symbols, data symbols and CRC bits are also transmitted on the chosen subband to form the whole control beacon. Here, we choose the ZC sequence [6] since it has ideal autocorrelation and optimum cross-correlation property [7]. Moreover, the ZC sequence has constant amplitude in both frequency and time domain, which brings the low peak-to-average power ratio advantage. The constant amplitude in frequency domain helps to achieve a good channel estimation, while the constant amplitude in time domain helps to reduce the requirement of the power amplifier of the AP.

The basic ZC sequence for the control beacon preamble using a single subband is $\{P_c[k]\}_{k=0}^{N_0-1}$, where k is the subcarrier index, N_0 is the size of subcarriers in each subband. When subband q is used for control beacon transmission, the ZC sequence is mapped to the corresponding subband, and we obtain the frequency domain symbol of the preamble as

$$S_q[k] = \begin{cases} \sqrt{Q}P_c[k-qN_0] & k \in \Omega_q \\ 0 & k \notin \Omega_q \end{cases}, \tag{1}$$

where Ω_q is the set of subcarriers in subbands q with $|\Omega_q| = N_0$, and the power factor Q makes the transmit power constant no matter whether the control beacon or the channel switching beacon is transmitted. As a whole, there are Q preambles for the control beacon. At the receiver, the conjugate of the preambles $\boldsymbol{S}_0, .., \boldsymbol{S}_q, .., \boldsymbol{S}_{Q-1}$ are saved in a candidate preamble pool for the preamble detection.

B. Preamble Detection for Control Beacon

At the receiver, the AWGN channel is considered. We assume i is the synchronized time index of the beacon signal, and the received signal is sampled into a vector $\boldsymbol{y}_i = [y(i), y(i+1), \ldots, y(i+N-1)]$, where N is the preamble length. To ease the derivation of the control beacon detection algorithm, we assume the synchronization is perfect at first. We will show the details about finding the accurate synchronization point of the beacon at last. Hence, we ignore the time index i, and calculate the N-point FFT of $\boldsymbol{y}$ to get the corresponding frequency domain samples $\boldsymbol{Y}$. We denote $Y(k)$ as the kth FFT output of $\boldsymbol{Y}$. Based on the frequency domain samples $\boldsymbol{Y}$, we need to detect whether there is a control beacon transmitted and which subband is used. The detection problem can be formulated as a binary hypothesis test:

$$\begin{aligned} \mathcal{H}_0 &: Y(k) = W(k) + I(k), \\ \mathcal{H}_1 &: Y(k) = S_q(k) + W(k) + I(k), \end{aligned} \tag{2}$$

where $k = 0, 1, \ldots, N-1$, $W(k)$ is the noise sample and $I(k)$ is the NBI sample. The noise on each subcarrier is modeled as a complex zero-mean Gaussian random variable with variance σ^2. Ω_I is the set of interfered subcarriers and the interference on interfered subcarrier is also modeled as a complex zero-mean Gaussian random variable with variance σ_I^2. Since the control beacon is transmitted on a subband which is not interfered, Ω_I is orthogonal to Ω_q. Hypotheses $\mathcal{H}_0$ represents the control beacon is not present. Hypotheses $\mathcal{H}_1$ represents the control beacon is aligned with the vector.

In (2), the used subband of the control beacon q, the interfered subband and the interference power of $I(k)$ are unknown at the receiver. The detection problem can be solved through GLRT. Since $I(k)$ is the same under each hypothesis, the GLRT decides $\mathcal{H}_1$ if

$$L_G(\boldsymbol{Y}) = \frac{p(\boldsymbol{Y};\hat{q},\mathcal{H}_1)}{p(\boldsymbol{Y};\mathcal{H}_0)} > \gamma, \tag{3}$$

where $\hat{q}$ is the MLE of q assuming $\mathcal{H}_1$ is true and

$$\begin{aligned} &p(\boldsymbol{Y};\hat{q},\mathcal{H}_1) \\ &= \prod_{\substack{k\notin\Omega_{\hat{q}} \\ k\notin\Omega_I}} \frac{1}{\sqrt{\pi\sigma^2}} \exp[-\frac{1}{\sigma^2}Y(k)Y^*(k)] \\ &\quad\times \prod_{k\in\Omega_{\hat{q}}} \frac{1}{\sqrt{\pi\sigma^2}} \exp[-\frac{1}{\sigma^2}(Y(k)-S_{\hat{q}}(k))(Y^*(k)-S_{\hat{q}}^*(k))] \\ &\quad\times \prod_{k\in\Omega_I} \frac{1}{\sqrt{\pi(\sigma^2+\sigma_I^2)}} \exp[-\frac{1}{\sigma^2+\sigma_I^2}Y(k)Y^*(k)], \end{aligned} \tag{4}$$

and

$$p(\boldsymbol{Y};\mathcal{H}_0) = \prod_{k\notin\Omega_I} \frac{1}{\sqrt{\pi\sigma^2}} \exp[-\frac{1}{\sigma^2}Y(k)Y^*(k)] \times \prod_{k\in\Omega_I} \frac{1}{\sqrt{\pi(\sigma^2+\sigma_I^2)}} \exp[-\frac{1}{\sigma^2+\sigma_I^2}Y(k)Y^*(k)]. \tag{5}$$

Substituting (4) and (5) into (3) and taking logarithms of $L_G(\boldsymbol{Y})$, we decide $\mathcal{H}_1$ if

$$\ln L_G(\boldsymbol{Y}) = \frac{2\mathcal{R}\{\sum_{k\in\Omega_{\hat{q}}} Y(k)S_{\hat{q}}^*(k)\} - \sum_{k\in\Omega_{\hat{q}}} S_{\hat{q}}(k)S_{\hat{q}}^*(k)}{\sigma^2} > \ln\gamma, \tag{6}$$

where $\mathcal{R}\{.\}$ denotes the real part, $\sum_{k\in\Omega_{\hat{q}}} S_{\hat{q}}(k)S_{\hat{q}}^*(k) = \varepsilon$, and we decide $\mathcal{H}_1$ if the equivalent test statistic

$$T(\boldsymbol{Y}) = \mathcal{R}\{\sum_{k\in\Omega_{\hat{q}}} Y(k)S_{\hat{q}}^*(k)\} > \frac{\varepsilon+\sigma^2\ln\gamma}{2} = \gamma', \tag{7}$$

where γ' is the threshold. We notice the test statistic is only related to the MLE of unknown used subband q and the parameters of $I(k)$ is unnecessary. Hence, the GLRT approach can also apply to the control beacon detection without interference. The MLE of q is the value that maximizes

$$\hat{q}_{ML} = \max_q p(\boldsymbol{Y}; q, \mathcal{H}_1). \tag{8}$$

In (4), for different q, the first product term and the third product term are the same. Hence, we just need to compare the second product term for different q, and equivalently, the MLE of q is the value that minimizes

$$\hat{q}_{ML} = \min_q \sum_{k\in\Omega_q} (Y(k) - S_q(k))(Y^*(k) - S_q^*(k)). \tag{9}$$

Further, equivalently, it is the value that maximizes

$$\hat{q}_{ML} = \max_q 2\mathcal{R}\{\sum_{k\in\Omega_q} Y(k)S_q^*(k)\} - \sum_{k\in\Omega_q} |Y(k)|^2. \tag{10}$$

The first term of (10) is the traditional correlator and the second term is the energy of the subband. The traditional correlator will estimate the interfered subband as the used subband if the NBI is strong. However, by subtracting the subband energy, the result of (10) for the used subband will outperform the interfered subband. After estimating the used subband, we use (7) to decide whether the control beacon is transmitted or not. The test statistic is a complex replica-correlator and the sum of independent complex Gaussian random variables is also a complex Gaussian random variable. Further, we can obtain that $E(T(\boldsymbol{Y});\mathcal{H}_0) = 0, var(T(\boldsymbol{Y});\mathcal{H}_0) = \sigma^2\varepsilon/2$, $E(T(\boldsymbol{Y});\mathcal{H}_1) = \varepsilon$ and $var(T(\boldsymbol{Y});\mathcal{H}_1) = \sigma^2\varepsilon/2$. Hence,

$$T(\boldsymbol{Y}) \sim \begin{cases} \mathcal{N}(0, \sigma^2\varepsilon/2) & \text{under } \mathcal{H}_0 \\ \mathcal{N}(\varepsilon, \sigma^2\varepsilon/2) & \text{under } \mathcal{H}_1 \end{cases} \tag{11}$$

and the detection performance can be easily obtained as

$$P_{FA} = Q\left(\frac{\gamma'}{\sqrt{\frac{\sigma^2\varepsilon}{2}}}\right), \quad P_D = Q\left(\frac{\gamma'-\varepsilon}{\sqrt{\frac{\sigma^2\varepsilon}{2}}}\right). \tag{12}$$

The detection threshold can be derived based on a fixed false alarm probability P_{FA}.

Here, we summarize the detection process. First, we use (10) to estimate the most possible used subband, then we use (7) to detect whether there is a control beacon transmission. Moreover, to remove the synchronization assumption, we just need to compare results of (7) in a observation window for different time index i, if the beacon detected and the maximum result related i is the estimated synchronization point.

After detecting the used subband, the channel coefficients are estimated through the training symbols. The data symbols mapped to the used subband can be decoded and verified, and the resource blocks allocation information can be obtained.

C. Design and Detection of Channel Switching Beacon

When there is WBI, the AP chooses to transmit the channel switching beacon with targeted switching channel information embedded. Since WBI may interfere all subbands of the channel, a longer ZC sequence $\{P_s[k]\}_{k=0}^{N-1}$ is transmitted on all subbands. The frequency domain symbol of the preamble is $S_Q[k] = P_s[k]$, the power factor is set as 1 to make the transmission power to be the same as the control beacon.

Under serious interference, the digital communication strategy is unreliable and easy to be interfered. We propose a very simple and reliable strategy to deliver the targeted switching channel information. As shown in Fig. 2 (b), the preamble $\boldsymbol{S_Q}$ is transmitted twice, and the distance between the two repeated preambles embeds the shared switching channel information. For example, we set the null samples between two repeated preambles $d = cd_0$, where d_0 is a basic distance, and c $(c = 1, 2..., C)$ is the targeted switching channel index. Here, we take advantage of the good correlation performance of the ZC sequence, and no information decoding is needed.

We add preamble $\boldsymbol{S_Q}$ into the candidate preamble pool, which has $Q+1$ possible preambles when a beacon is transmitted, including Q control beacon preambles and one channel switching beacon preamble. When detecting the channel switching beacon preamble, a similar MLE estimator as (10) is used. Different from (10), the first term is the correlation for all subcarriers, and the second term is the channel energy divide by Q. The switching channel can be obtained by estimating the distance between two peaks. Nevertheless, since the distance $(d = cd_0)$ between two preambles has only C possibilities, after the first switching preamble detected and located, we just calculate $T(\boldsymbol{Y})$ for all possible distances d and compare the results, the one with largest value is the corresponding targeted switching channel.

IV. Performance Evaluation

In this section, the performance of the control beacon preamble detection with lower signal-to-noise ratios (SNRs) under NBI is evaluated through simulations. Moreover, we also evaluate the adaptive beacon transmission on a software defined radio (SDR) platform. Fixed beacon transmission (FBT) always using all subbands is implemented to compare the performance with our proposed adaptive beacon transmission (ABT). For each evaluation, we repeat 10^6 times to evaluate the performance. The carrier frequency is in the range of the ISM band. The number of channels (C) is 10,

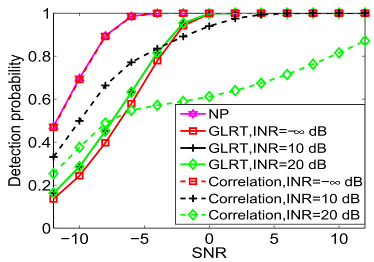

Fig. 3. GLRT detection with $P_{FA} = 0.01$.

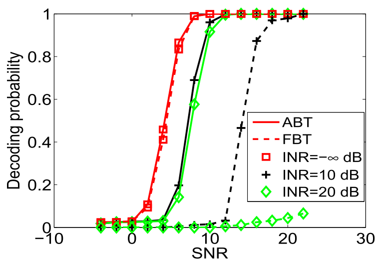

Fig. 4. Decoding of control beacon.

and channel bandwidth is 5 MHz. The number of subcarriers in each channel (N) is 256. The number of subbands in each channel (Q) is 5 and each subband consists of 51 subcarriers (N_0). The CP size of each OFDM data symbol is 32. The basic distance d_0 for channel switching is 64. The control beacon packet adopts BPSK as the modulation scheme.

In Fig. 3, the performance of beacon preamble detection versus different SNRs with different interference power of NBI is evaluated through simulations. We define $SNR = \frac{\sigma_s^2}{\sigma^2}$, where σ_s^2 is the average power on the used subcarriers of beacon packet, and $INR = \frac{\sigma_I^2}{\sigma^2}$, where $INR = -\infty$ dB represents no NBI. The GLRT detection performance is shown in Fig. 3, the detection threshold is calculated by (12) given $P_{FA} = 0.01$. We can see the detection probability of GLRT approach is slightly worse than the Neyman-Pearson (NP) approach with known used subband. The estimation error of (10) results in the performance gap. When no NBI exists, the performance of correlation method is better. However, the detection probability of GLRT approach performs much better than the traditional correlation method when facing strong NBI ($INR = 20$ dB) and it is close to 100% when SNR exceeds 0 dB. Since the SNR of control beacon is usually larger than 0 dB for reliable decoding, the detection performance of GLRT approach is effective for reliable control beacon transmission.

In Fig. 4, the performance of control beacon transmission under NBI is evaluated through experiments. After used subband detected, the beacon packet is decoded, and CRC bits are used to check the validity of the packet. Fig. 4 shows the control beacon packet correct decoding probability of ABT and FBT, because of the orthogonal subband utilization used for ABT, the interference has small influence and the decoding probability achieves close to 100% with reasonable SNR (10 dB). However, the FBT losts most beacon packets under NBI.

In Fig. 5, we evaluate the successful probability of channel switching versus different SNRs with different interference

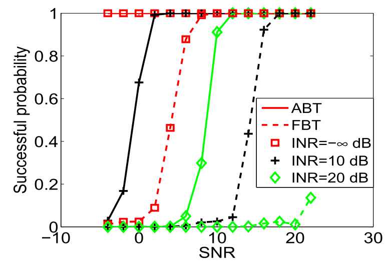

Fig. 5. Probability of channel switching.

power of WBI through experiments. For the ABT, channel switching is successful when both the first channel switching preamble is detected and the embedded switching channel is extracted correctly. For the FBT, it is successful when the channel switching beacon is decoded correctly. Since the beacon signal is not orthogonal with interference, the strong interference power has a obvious negative influence on the performance. However, as we can see from Fig. 5, the ABT outperforms FBT because it has a more reliable information transmission strategy. Moreover, for the ABT, the successful switching probability increases obviously with SNR. Hence, to guarantee the absolutely reliable channel switching beacon transmission for industrial applications, power control strategy can be adopted by the AP to combat the high power interference. The interference power can be estimated by the AP at the interference detection step, then the AP adjusts the transmission power of the channel switching beacon to let $SNR - INR \geq X$. Based on experimental results, we can set $X = -10$ dB, which is a conservative value to ensure successful channel switching.

V. Conclusion

In this letter, two different beacons are adaptively used in the Cognitive-OFDM IWN for sharing different information under different interference. The preambles of beacons are specifically designed to help the receivers to extract the shared information. The beacon detection and decoding algorithm are provided. The adaptive beacon transmission strategy has been evaluated, and the performance of detection and decoding can achieve close to 100% even under serious interferences.

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