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Anti-interference performance analysis of frequency-shift filter in scenario of multiple WPANs accessing HAN

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Abstract: In the scenario of multiple wireless personal area networks (WPANs) accessing the home area network (HAN), the frequency-shift (FRESH) filter based on the cyclostationary theory is applied for the anti-interference at the 2.4 GHz spectrum. The main architecture of multiple WPANs accessing the HAN is proposed. The medium access control (MAC)-level coordination solution applied in the access point (AP) for the coexistence of different communication protocols within WPAN is discussed. The diagram of the adaptive FRESH filter is described. The anti-interference models of the FRESH filter in the scenario of multiple WPANs accessing the HAN are proposed. The minimum mean square error (MMSE) convergence property of the FRESH filter with the change in the data point number is analyzed. The simulation results indicate that the FRESH filter can effectively extract the signal of interest (SOI) from the interference with the partly overlapped spectrum. Thus, the excellent anti-interference performance of the FRESH filter is validated. Moreover, by both theoretical analysis and simulation, the MMSE convergent property of the FRESH filter is also proven.

Key words: cyclostationary; frequency-shift filter; anti-interference; wireless personal area networks; home area network; minimum mean square error

The wireless personal area network (WPAN) allows personal electronic devices such as laptops, cell phones, personal digital assistants (PDA), etc. to connect within a short distance (1 to 100 m) and to communicate without wired connections. One key advantage of the WPAN is the manner in which ad hoc connections can be easily and transparently established among a large number of heterogeneous devices[1]. There are many kinds of wireless technologies which can be used to build a WPAN such as Bluetooth, Zigbee, IEEE 802.11, etc. The home area network (HAN) consists of several networked devices and home appliances (such as washers, air-conditioners, water heaters, etc.) connected to each other[2]. The devices in HAN can usually access public networks for sharing more resources and providing the real-time running state to remote users. The connection between the HAN and public networks such as the Internet is usually provided by a HAN gateway.

The WPAN provides an access point[3] (AP) for personal devices to be able to access the HAN. There are many advantages for the WPAN to access the HAN. First, personal devices in the WPAN are often used at home. Therefore, it makes the WPAN possible and convenient to access the HAN. Secondly, the WPAN's accessing the HAN not only results in connection between WPAN devices and HAN devices but also results in WPAN devices accessing public networks such as the Internet by a HAN gateway for sharing various streaming multimedia. Finally, WPAN devices often have small storage and low computation speed and the HAN gateway usually has better hardware and software configurations. If WPAN devices access public networks via their own AP, a better hardware and software configuration will be required for every AP. When WPAN devices access into public networks by a HAN gateway instead of their own AP, the limited hardware and software resources of the AP can be used to provide better performance of networking and central control.

This paper focuses on the application of the frequency-shift (FRESH) filter in the scenario of multiple WPANs accessing the HAN for anti-interference at the 2.4 GHz spectrum based on different cyclostationary characteristics of different signals.

A complex-valued time-series $x(t)$ is said to exhibit wide-sense (second-order) cyclostationarity with cycle frequency $\alpha \neq 0$ if and only if the cyclic autocorrelation function[4]

$$R_x^{\alpha}(\tau) = \left\langle x\left(t+\frac{\tau}{2}\right) x^*\left(t-\frac{\tau}{2}\right) \mathrm{e}^{-\mathrm{j}2\pi\alpha t} \right\rangle \tag{1}$$

exists and is not zero for some values of τ. In Eq. (1), $\langle \cdot \rangle$ denotes average over all time t; τ denotes the lag parameter.

In this paper, the main architecture of multiple WPANs accessing the HAN and the medium access control (MAC) level coordination solution applied in the AP for the coexistence of different communication protocols within the WPAN are discussed. The diagram of the adaptive FRESH filter is described. The anti-interference models of the FRESH filter for extracting Zigbee from the IEEE 802.11b interference and for extracting IEEE 802.11b from the frequency hopping spread spectrum (FHSS) interference are proposed, respectively. It can be known from simulation results that the FRESH filter has an excellent anti-interference performance in the scenario of multiple WPANs accessing a HAN. Furthermore, the minimum mean square error (MMSE) convergent property of the FRESH filter is analyzed. By both theoretical analysis and simulation, it can be proven that the N-sample time-average realization of MMSE converges in the mean-square sense to its real value at the

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rate of $O(1/N)$ where N is the data point number obtained in practical communications.

1 Multiple WPANs Accessing HAN

1.1 Main architecture

As shown in Fig. 1, the HAN consists of a gateway which connects all home devices such as digital TVs, washers, etc. in a wired or a wireless way. Multiple WPANs in different locations access the HAN by their own AP which connects with the HAN gateway wirelessly.

The HAN gateway provides functions that range from central control of home devices to the interaction with public networks. In the WPAN, the AP can be a WPAN device or a fixed device (Fig. 1 indicates the second situation). The WPAN is networked via an ad hoc mode so that personal devices can freely access or leave the WPAN at any time.

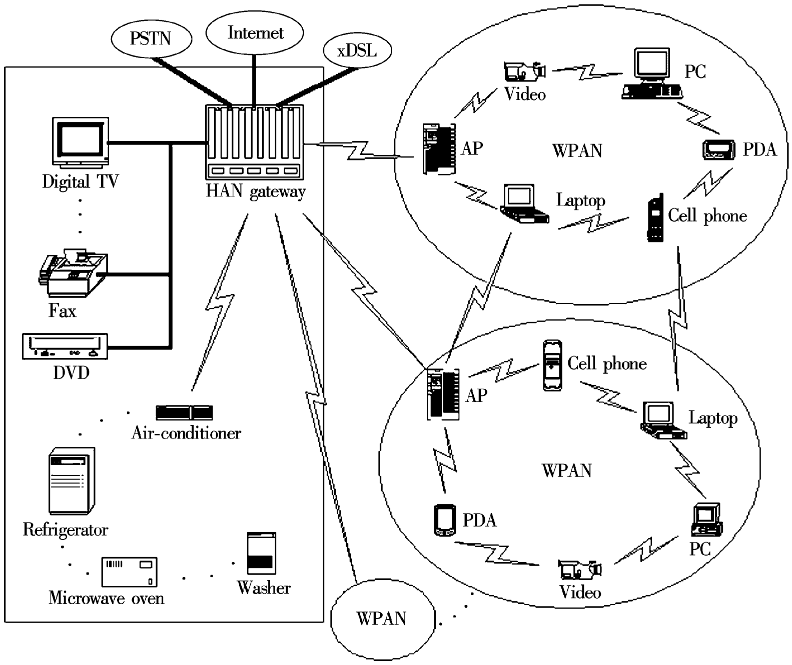

Fig. 1 Main architecture of multiple WPANs accessing HAN

1.2 MAC-level coordination solution

No single wireless communication technology can sufficiently satisfy all the devices in the WPAN because different devices have different demands on the transmission speed, the working power, the cost, etc.. However, the coexistence of various wireless communication technologies within the WPAN may lead to a serious mutual interference problem[5]. Therefore, it is essential for the AP to make multiple wireless communication protocols compatible. There have been many techniques for harmonizing radio frequencies (RF) such as multi-mode RF coordination and driver-level coordination. These two techniques have obvious weaknesses such as decreasing device performance, leading to data packets collisions and worsening system throughput. To achieve the coexistence of multiple wireless communication protocols within the WPAN, the smart and seamless coordination at the MAC layer[6] of these protocols is adopted. This MAC-level coordination solution exchanges the information and manages sending/receiving operations at the MAC layer. It is operated in the baseband at a pretty high rate.

Fig. 2 shows the diagram of the MAC-level coordination solution applied in the AP. MAC processing chips of IEEE 802.11b, Bluetooth and Zigbee are mutually connected by the universal coexistence interface bus. When IEEE 802.11b, Bluetooth and Zigbee need transmission bandwidths simultaneously, the AP uses multiplexing techniques to allocate the bandwidths. Thus, the AP is able to satisfy the communication requests of devices adopting different communication protocols within the WPAN.

2 FRESH Filter for Anti-Interference in Scenario of WPANs Accessing HAN

In our senario of multiple WPANs accessing the HAN, there are a large number of wireless devices working at the 2.4 GHz spectrum. Mutual interference occurs between WPAN devices and HAN devices. It also occurs among different WPANs. How to reduce or avoid these mutual interferences becomes extremely important.

2.1 Adaptive FRESH filter

We apply the adaptive FRESH filter for the anti-interference in the scenario of multiple WPANs accessing a HAN. According to the cyclostationary theory, most of the modulated signals have characteristics of being cyclostationary[7]. Based on the cyclic Wiener filter theory[8], the adaptive FRESH filter can be designed as shown in Fig. 3.

The discrete form of the received signal is given by

$$r(n) = s(n) + i(n) + w(n) \tag{2}$$

where $s(n)$ and $i(n)$ are the signal of interest (SOI) and the interference, respectively; $w(n)$ is the Gaussian white noise. They are assumed to be mutually independent.

The output of the FRESH filter is given in a matrix form by

$$\hat{s}(n) = \boldsymbol{h}^{\mathrm{H}} \hat{\boldsymbol{r}}(n) \tag{3}$$

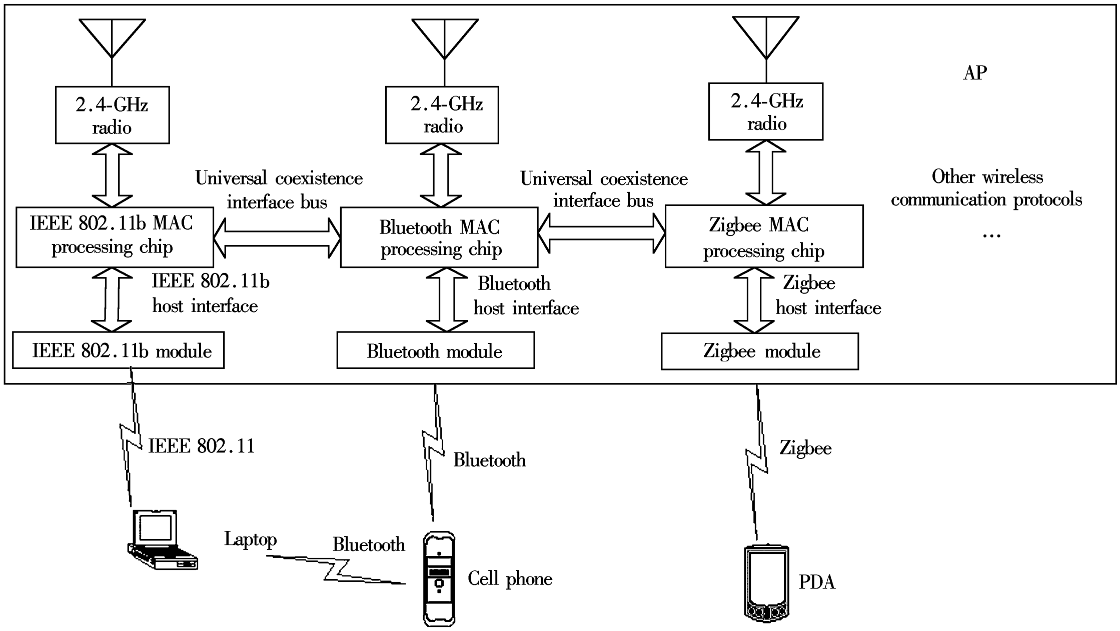

Fig. 2 MAC-level coordination solution applied in AP

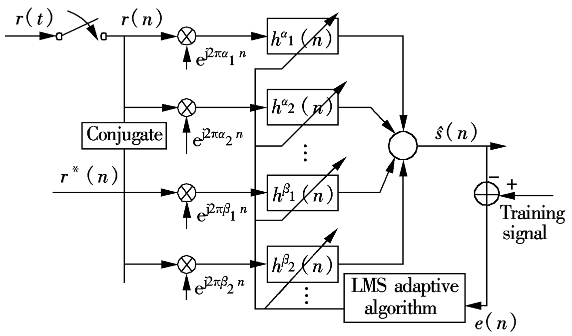

Fig. 3 Diagram of the adaptive FRESH filter

where

$$\boldsymbol{h} = \{h_{\alpha_1}^{\mathrm{T}}, \ldots, h_{\alpha_P}^{\mathrm{T}}, h_{\beta_1}^{\mathrm{T}}, \ldots, h_{\beta_Q}^{\mathrm{T}}\}^{\mathrm{T}}$$

$$\hat{\boldsymbol{r}}(n) = \{\hat{\boldsymbol{r}}_{\alpha_1}^{\mathrm{T}}(n), \ldots, \hat{\boldsymbol{r}}_{\alpha_P}^{\mathrm{T}}(n), \hat{\boldsymbol{r}}_{\beta_1}^{\mathrm{T}}(n), \ldots, \hat{\boldsymbol{r}}_{\beta_Q}^{\mathrm{T}}(n)\}^{\mathrm{T}}$$

Here

$$\boldsymbol{h}_{\alpha_p} = \{h^{\alpha_p}(0), h^{\alpha_p}(1), \ldots, h^{\alpha_p}(L_p - 1)\}^{\mathrm{T}} \quad p = 1, 2, \ldots, P$$

$$\hat{\boldsymbol{r}}_{\alpha_p}(n) = \{r(n)\mathrm{e}^{\mathrm{j}2\pi\alpha_p n}, \ldots, r(n - L_p + 1)\mathrm{e}^{\mathrm{j}2\pi\alpha_p(n - L_p + 1)}\}^{\mathrm{T}} \quad p = 1, 2, \ldots, P$$

are the frequency-shifting linear paths and

$$\boldsymbol{h}_{\beta_q} = \{h^{\beta_q}(0), h^{\beta_q}(1), \ldots, h^{\beta_q}(M_q - 1)\}^{\mathrm{T}} \quad q = 1, 2, \ldots, Q$$

$$\hat{\boldsymbol{r}}_{\beta_q}(n) = \{r(n)\mathrm{e}^{\mathrm{j}2\pi\beta_q n}, \ldots, r(n - M_q + 1)\mathrm{e}^{\mathrm{j}2\pi\beta_q(n - M_q + 1)}\}^{\mathrm{T}} \quad q = 1, 2, \ldots, Q$$

are the frequency-shifting conjugate linear paths. α_p and β_q are cycle frequencies of $s(n)$. P and Q are the number of the linear paths and the conjugate linear paths, respectively. $\boldsymbol{h}$ and $\hat{\boldsymbol{r}}(n)$ are both K-dimensional vectors,

$$K = \sum_{p=1}^{P} L_p + \sum_{q=1}^{Q} M_q \tag{4}$$

where L_p and M_q denote the lengths of the finite impulse response (FIR) filters $\boldsymbol{h}^{\alpha_p}(n)$ and $\boldsymbol{h}^{\beta_q}(n)$, respectively.

To obtain MMSE, the least mean square (LMS) adaptive algorithm is used to update the weight vectors of the filter. The K-dimensional weight vectors are calculated by

$$e(n) = d(n) - \boldsymbol{h}^{\mathrm{H}}\hat{\boldsymbol{r}}(n) \tag{5}$$

$$\boldsymbol{h} = \boldsymbol{h} + \mu(n)\hat{\boldsymbol{r}}(n)e^{*}(n) \tag{6}$$

where $\mu(n)$ is the step size of the LMS algorithm and $d(n)$ is the training signal.

2.2 Anti-interference models of FRESH filter

There are many kinds of wireless communication technologies working at the 2.4 GHz spectrum. To validate the anti-interference performance of the FRESH filter in the scenario of multiple WPANs accessing a HAN, we propose the anti-interference models of the FRESH filter for extracting Zigbee from the IEEE 802.11b interference and for extracting IEEE 802.11b from the FHSS interference, respectively. See Fig. 4 and Fig. 5.

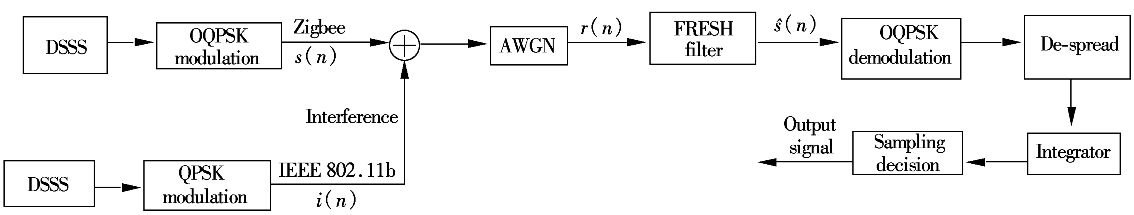

Fig. 4 Anti-interference model of FRESH filter for extracting Zigbee from IEEE 802.11b interference

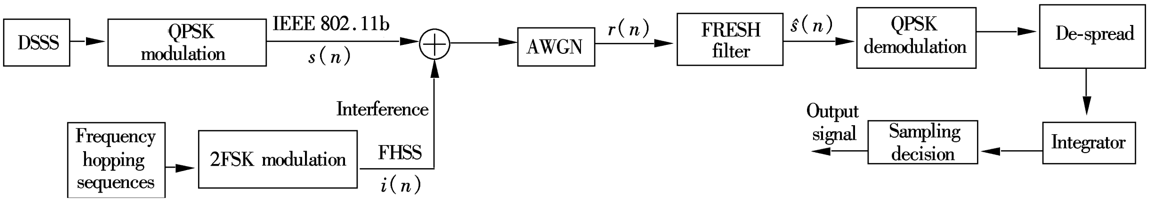

Fig. 5 Anti-interference model of FRESH filter for extracting IEEE 802. 11b from FHSS interference

Fig. 4 shows the anti-interference model of the FRESH filter for extracting Zigbee from the IEEE 802. 11b interference. As shown in Fig. 4, the IEEE 802. 11b signal is considered as the interference $i(n)$ which is produced by the direct sequence spread spectrum (DSSS) and the quadrature phase shift keying (QPSK) modulation. Zigbee signal is the SOI $s(n)$ produced by the DSSS and the offset quadrature phase shift keying (OQPSK) modulation. They are mixed by an adder and pass the additive white Gaussian noise (AWGN) channel to produce the receiving signal $r(n)$. At the receiving end, the receiving signal $r(n)$ is first processed by the adaptive FRESH filter and $\hat{s}(n)$ is obtained. Finally, we obtain the estimated Zigbee signal by operations of the OQPSK demodulation, the de-spread processing and the integral decision, respectively.

Fig. 5 shows the anti-interference model of the FRESH filter for extracting IEEE 802. 11b from the FHSS interference. FHSS signals in the scenario of multiple WPANs accessing the HAN include Bluetooth, HomeRF and other FHSS devices (spectrum coreless phones, medical devices, etc.). Bluetooth, HomeRF and those FHSS devices have different frequency hopping rates and different information rates. They can be considered as pseudo-random single-frequency interference or multi-frequencies interference[9]. As shown in Fig. 5, the FHSS interference $i(n)$ is produced by the frequency hopping sequences and the binary frequency shift keying (2FSK) modulation. IEEE 802. 11b signal is considered as SOI $s(n)$ which is produced by the DSSS and the QPSK modulation. They are mixed by an adder and pass the AWGN channel to produce the receiving signal $r(n)$. At the receiving end, the receiving signal $r(n)$ is first processed by the adaptive FRESH filter and $\hat{s}(n)$ is obtained. Finally, we obtain the estimated IEEE 802. 11b signal by operations of the QPSK demodulation, the de-spread processing and the integral decision, respectively.

3 MMSE Convergent Property of FRESH Filter

According to the principle of orthogonality, this optimum FRESH filter is given by

$$\boldsymbol{h}_{\text{opt}} = \boldsymbol{R}_{\hat{r}\hat{r}}^{-1}\boldsymbol{r}_{\hat{r}d} \tag{7}$$

where $\boldsymbol{R}_{\hat{r}\hat{r}}(N) = E[\hat{\boldsymbol{r}}(n)\hat{\boldsymbol{r}}^{\text{H}}(n)]$, $r_{\hat{r}d}(N) = E[\hat{\boldsymbol{r}}(n)d^*(n)]$.

The MMSE of the FRESH filter is given by

$$\xi_{\text{opt}} = r_d(0) - \boldsymbol{r}_{\hat{r}d}^{\text{H}}\boldsymbol{R}_{\hat{r}\hat{r}}^{-1}\boldsymbol{r}_{\hat{r}d} \tag{8}$$

where $r_d(0) = E[d(n)d^*(n)]$.

As the samples obtained in the practical communications are finite, the MMSE performance with finite data points needs to be analyzed.

Suppose that N samples are obtained, then the N-sample time-average realizations of $\boldsymbol{h}_{\text{opt}}$ and ξ_{opt} are given by

$$\boldsymbol{h}_{\text{opt}}(N) = \boldsymbol{R}_{\hat{r}\hat{r}}^{-1}(N)\boldsymbol{r}_{\hat{r}d}(N) \tag{9}$$

$$\xi_{\text{opt}}(N) = r_r(0)(N) - \boldsymbol{r}_{\hat{r}d}^{\text{H}}(N)R_{\hat{r}\hat{r}}^{-1}(N)\boldsymbol{r}_{\hat{r}d}(N) \tag{10}$$

where $\boldsymbol{R}_{\hat{r}\hat{r}}(N) = \frac{1}{N}\sum_{n=1}^{N}\hat{\boldsymbol{r}}(n)\hat{\boldsymbol{r}}^{\text{H}}(n)$, $\boldsymbol{r}_{\hat{r}d}(N) = \frac{1}{N}\sum_{n=1}^{N}\hat{\boldsymbol{r}}(n)d^*(n)$, $r_d(0)(N) = \frac{1}{N}\sum_{n=1}^{N}d(n)d^*(n)$.

To obtain the theorem below which shows the convergent property of MMSE with finite data points, we introduce the consistent norm $\|\ \|$ in the matrix theory[10]. It is defined as

$$\|\boldsymbol{x}\| = (\boldsymbol{x}^{\text{H}}\boldsymbol{x})^{1/2}$$

$$\|\boldsymbol{A}\| = \max_{\|\boldsymbol{x}\|=1}(\|\boldsymbol{A}\boldsymbol{x}\|)$$

where $\boldsymbol{x}$ and $\boldsymbol{A}$ are the vector and the matrix in the complex field, respectively.

Theorem The N-sample time-average realization of MMSE $\xi_{\text{opt}}(N)$ converges in the mean-square sense to its real value ξ_{opt} at the rate of $O(1/N)$.

Proof Two inequalities of the consistent norm are needed:

$$\|\boldsymbol{u}^{\text{H}}\boldsymbol{v}\|^2 \leqslant \|\boldsymbol{u}\|^2\|\boldsymbol{v}\|^2$$

$$\|\boldsymbol{u}+\boldsymbol{v}\|^2 \leqslant 2\|\boldsymbol{u}\|^2 + 2\|\boldsymbol{v}\|^2$$

where $\boldsymbol{u}$ and $\boldsymbol{v}$ are vectors in the complex field.

$$\begin{aligned}E[\|r_d(0)(N) - r_d(0)\|^2] &= E\Big\{\frac{1}{N}\sum_{n=1}^{N}[d(n)d^*(n) - r_d(0)]\frac{1}{N}\sum_{m=1}^{N}[d(m)d^*(m) - r_d(0)]^*\Big\} = \\ &E\Big\{\frac{1}{N^2}\sum_{n=1}^{N}[d(n)d^*(n) - r_d(0)][d(n)d^*(n) - r_d(0)]^*\Big\} + \\ &E\Big\{\frac{1}{N^2}\sum_{\substack{n,m=1\\ n\neq m}}^{N}[d(n)d^*(n) - r_d(0)][d(m)d^*(m) - r_d(0)]^*\Big\} = \\ &\frac{1}{N}E\{[d(n)d^*(n) - r_d(0)][d(n)d^*(n) - r_d(0)]^*\}\end{aligned} \tag{11}$$

From Eq. (11), we have

$$E[\|r_d(0)(N) - r_d(0)\|^2] = O\Big(\frac{1}{N}\Big) \tag{12}$$

From Ref. [11], it can be known that

$$E[\|\boldsymbol{r}_{\hat{r}d}(N) - \boldsymbol{r}_{\hat{r}d}\|^2] = O\Big(\frac{1}{N}\Big) \tag{13}$$

$$E[\|\boldsymbol{R}_{\hat{r}\hat{r}}^{-1}(N)\boldsymbol{r}_{\hat{r}d}(N) - \boldsymbol{R}_{\hat{r}\hat{r}}^{-1}\boldsymbol{r}_{\hat{r}d}\|^2] = O\Big(\frac{1}{N}\Big) \tag{14}$$

$$\begin{aligned}E[\|\boldsymbol{r}_{\hat{r}d}^{\text{H}}\boldsymbol{R}_{\hat{r}\hat{r}}^{-1}\boldsymbol{r}_{\hat{r}d} - \boldsymbol{r}_{\hat{r}d}^{\text{H}}(N)\boldsymbol{R}_{\hat{r}\hat{r}}^{-1}(N)\boldsymbol{r}_{\hat{r}d}(N)\|^2] = \\ E\{\|[\boldsymbol{r}_{\hat{r}d}^{\text{H}} - \boldsymbol{r}_{\hat{r}d}^{\text{H}}(N)]\boldsymbol{R}_{\hat{r}\hat{r}}^{-1}(N)\boldsymbol{r}_{\hat{r}d}(N) +\end{aligned}$$

$$\begin{aligned}&\boldsymbol{r}_{\hat{r}d}^{\mathrm{H}}[\boldsymbol{R}_{\hat{r}\hat{r}}^{-1}\boldsymbol{r}_{\hat{r}d}-\boldsymbol{R}_{\hat{r}\hat{r}}^{-1}(N)\boldsymbol{r}_{\hat{r}d}(N)]\ \|^{2}\}\leqslant\\&2E\{\ \|\ [\boldsymbol{r}_{\hat{r}d}^{\mathrm{H}}-\boldsymbol{r}_{\hat{r}d}^{\mathrm{H}}(N)]\boldsymbol{R}_{\hat{r}\hat{r}}^{-1}(N)\boldsymbol{r}_{\hat{r}d}(N)\ \|^{2}\}+\\&2E\{\ \|\ \boldsymbol{r}_{\hat{r}d}^{\mathrm{H}}[\boldsymbol{R}_{\hat{r}\hat{r}}^{-1}\boldsymbol{r}_{\hat{r}d}-\boldsymbol{R}_{\hat{r}\hat{r}}^{-1}(N)\boldsymbol{r}_{\hat{r}d}(N)]\ \|^{2}\}\leqslant\\&2E\{\ \|\ \boldsymbol{r}_{\hat{r}d}-\boldsymbol{r}_{\hat{r}d}(N)\ \|^{2}\ \|\ \boldsymbol{R}_{\hat{r}\hat{r}}^{-1}(N)\boldsymbol{r}_{\hat{r}d}(N)\ \|^{2}\}+\\&2E\{\ \|\ \boldsymbol{r}_{\hat{r}d}\ \|^{2}\ \|\ \boldsymbol{R}_{\hat{r}\hat{r}}^{-1}\boldsymbol{r}_{\hat{r}d}-\boldsymbol{R}_{\hat{r}\hat{r}}^{-1}(N)\boldsymbol{r}_{\hat{r}d}(N)\ \|^{2}\}\end{aligned}\qquad(15)$$

Using the boundedness of $\|\boldsymbol{R}_{\hat{r}\hat{r}}^{-1}(N)\boldsymbol{r}_{\hat{r}d}(N)\|^2$ and $\|\boldsymbol{r}_{\hat{r}d}\|^2$ together with Eqs. (13) and (14), it can be concluded that

$$E[\ \|\ \boldsymbol{r}_{\hat{r}d}^{\mathrm{H}}\boldsymbol{R}_{\hat{r}\hat{r}}^{-1}\boldsymbol{r}_{\hat{r}d}-\boldsymbol{r}_{\hat{r}d}^{\mathrm{H}}(N)\boldsymbol{R}_{\hat{r}\hat{r}}^{-1}(N)\boldsymbol{r}_{\hat{r}d}(N)\ \|^{2}]=O\left(\frac{1}{N}\right)\qquad(16)$$

$$\begin{aligned}&E[\ \|\xi_{\mathrm{opt}}(N)-\xi_{\mathrm{opt}}\|^{2}]=E\{\ \|\ \boldsymbol{r}_{d}(0)(N)-\boldsymbol{r}_{\hat{r}d}^{\mathrm{H}}(N)\boldsymbol{R}_{\hat{r}\hat{r}}^{-1}(N)\cdot\\&\quad\boldsymbol{r}_{\hat{r}d}(N)-[\,r_{d}(0)-\boldsymbol{r}_{\hat{r}d}^{\mathrm{H}}\boldsymbol{R}_{\hat{r}\hat{r}}^{-1}\ \boldsymbol{r}_{\hat{r}d}]\ \|^{2}\}\leqslant\\&\quad2E\{\ \|\ \boldsymbol{r}_{d}(0)(N)-r_{d}(0)\ \|^{2}\}+\\&\quad2E\{\ \|\ \boldsymbol{r}_{\hat{r}d}^{\mathrm{H}}\boldsymbol{R}_{\hat{r}\hat{r}}^{-1}\boldsymbol{r}_{\hat{r}d}-\boldsymbol{r}_{\hat{r}d}^{\mathrm{H}}(N)\boldsymbol{R}_{\hat{r}\hat{r}}^{-1}(N)\boldsymbol{r}_{\hat{r}d}(N)\ \|^{2}\}\end{aligned}\qquad(17)$$

From Eqs. (12) and (16), we have

$$E[\ \|\ \xi_{\mathrm{opt}}(N)-\xi_{\mathrm{opt}}\ \|^{2}]=O\left(\frac{1}{N}\right)\qquad(18)$$

This theorem indicates that the MMSE of the FRESH filter converges in the mean-square sense to its real value at the rate of $O(1/N)$. Therefore, if the data point number obtained in the practical communication system is great enough, MMSE will be very close to its optimal value.

4 Simulation Results

4.1 Simulations of anti-interference performance

All the simulations of the anti-interference performance for the FRESH filter are carried out by Matlab Simulink tool in the equivalent baseband condition.

In the simulation of the anti-interference model for extracting Zigbee from the IEEE 802. 11b interference, the parameters are set as below: The rate and the central frequency of the Zigbee signal are set to be 250 kbit/s and 2. 430 GHz; the rate and the central frequency of the IEEE 802. 11b signal are set to be 2 Mbit/s and 2. 442 GHz; orders of every FIR filter are all chosen to be 11; the signal to noise ratio (SNR) of the AWGN channel is set to be 10 dB. The FRESH filter adopts the LMS adaptive algorithm. The spectrum of the mixed signal and the spectrum of the estimated Zigbee signal are shown in Fig. 6. Here, we assume that the power of the Zigbee signal and the power of the IEEE 802. 11b signal are at the same level.

From the spectrum comparison, it can be known that the adaptive FRESH filter is effective in extracting the Zigbee signal which is partly interfered with by the IEEE 802. 11b signal at the 2. 4 GHz spectrum.

In the simulation of the anti-interference model for extracting IEEE 802. 11b from the FHSS interference, the parameters are set as below: The rate and the central frequency of the IEEE 802. 11b signal are set to be 2 Mbit/s and 2. 442 GHz; the frequency hopping sequence is a random sequence with a rate of 200 hop/s; the two frequency points are set to be 2. 442 9 and 2. 441 7 GHz; orders of every FIR filter are all chosen to be 11; the SNR of the AWGN channel is set to be 10 dB. The FRESH filter adopts the LMS adaptive algorithm. The spectrum of the mixed signal and the spectrum of the estimated IEEE 802. 11b signal are shown in Fig. 7.

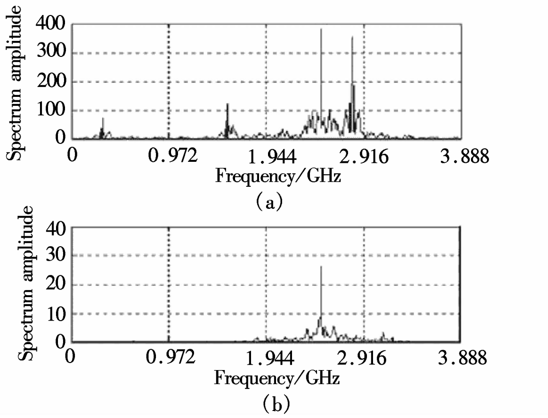

Fig. 6 Anti-interference performance of FRESH filter for extracting Zigbee signal from IEEE 802. 11b interference. (a) Mixed signal; (b) Estimated Zigbee signal

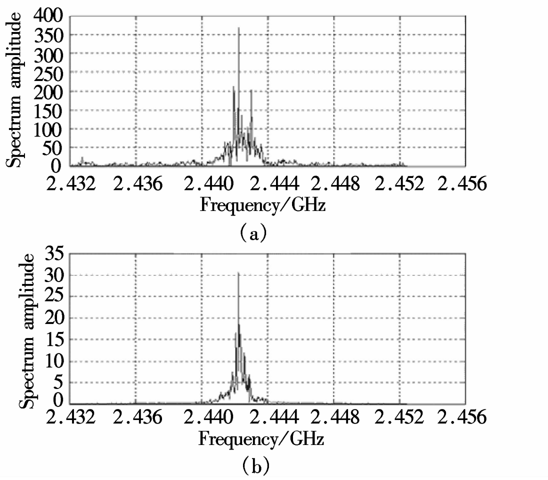

Fig. 7 Anti-interference performance of FRESH filter for extracting IEEE 802. 11b signal from FHSS interference. (a) Mixed signal; (b) Estimated IEEE 802. 11b signal

From the spectrum comparison, it can be known that the adaptive FRESH filter is effective in extracting the IEEE 802. 11b signal which is partly interfered with by the FHSS signal at the 2. 4 GHz spectrum.

4.2 Simulation of MMSE convergence property

The MMSE convergence property of the FRESH filter is shown in Fig. 8. In the simulation, ξ_{opt} is determined by calculating the time average of 2 000 data samples. The Y-axis denotes the normalized mean square error, given by $E\{\ \|\ \xi_{\mathrm{opt}}-\xi_{\mathrm{opt}}(N)\ \|^{2}\}/E\{\ \|\ \xi_{\mathrm{opt}}\ \|^{2}\}$. Every value is calculated by averaging ten independent simulation results. As shown in Fig. 8, the curve with " + " denotes that the normalized mean square error converges as the data point number increases. The curve with " * " converges at the rate of c/N(c is a selected constant). It is clearly observed that these two curves have a consistent convergence rate. As proven in our theorem, $\xi_{\mathrm{opt}}(N)$ converges in the mean square sense to its real value at the rate of $O(1/N)$.

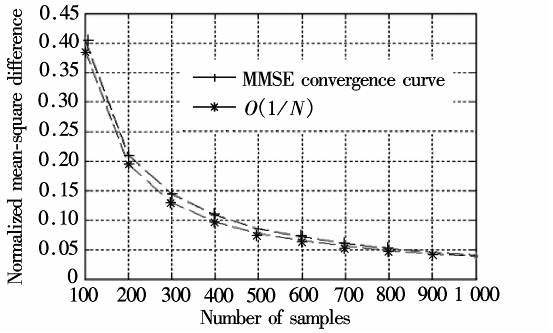

Fig. 8 MMSE convergence property of the FRESH filter

5 Conclusion

In this paper, the FRESH filter is applied in the scenario of multiple WPANs accessing a HAN for the anti-interference at the 2. 4 GHz spectrum. It can be known from the simulation results that the FRESH filter has an excellent anti-interference performance. Furthermore, the MMSE convergence property of the FRESH filter with the change in the data point number is theoretically analyzed. The simulation results indicate that if the data point number obtained in the practical communication system is great enough, MMSE of the FRESH filter will be very close to its optimal value.

The FRESH filter solution to the mutual interference problem at the 2. 4 GHz spectrum allows an anti-interference mechanism to work at the device end. It can be used in a mass mutual interference environment. The FRESH filter can be designed in the form of plug and play (PNP) so that WPAN devices can use it easily. It indicates an optimistic application prospect.

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多个无线个域网接入家域网场景的频移滤波器抗干扰性能分析

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摘要:在多个无线个域网(wireless personal area network,WPAN)接入家域网(home area network,HAN)场景中,应用基于循环平稳理论的频移滤波器实现2. 4 GHz 频段的抗干扰. 描述了多个无线个域网接入家域网的总体结构,讨论了应用于接入点的媒体访问控制(medium access control,MAC)级协作解决方案以保证多个无线通信协议共存于一个无线个域网内,给出了自适应频移滤波器的框图,提出了在多个无线个域网接入家域网场景中频移滤波器的抗干扰模型,分析了频移滤波器最小均方误差随数据积累点数变化的收敛性能. 仿真结果表明应用频移滤波器能够从谱重叠干扰中有效地提取有用信号,从而论证了频移滤波器优良的抗干扰性能. 此外,仿真还论证了由理论分析得出的频移滤波器最小均方误差的收敛特性.

关键词:循环平稳;频移滤波器;抗干扰;无线个域网;家域网;最小均方误差

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