Research Article

Multistandard Receiver Design for Telemedicine Monitoring System

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In short-distance wireless communications for telemedicine monitoring, different medical data measurement equipment has different wireless transmission modes. A multistandard receiver is designed that can adapt to different medical data measuring equipment. Using a second-order bandpass sampling for the design of antialiasing filters, two aliasing signals can be separated. Simultaneously, constraint conditions for sampling frequency are not as critical. The design is useful for a multistandard receiver in a telemedicine monitoring system and has the advantages such as saving spectrum resources and facilitating spectrum planning.

1. Introduction

With the rapid development of Internet of things technology and short-distance wireless communications technology, telemedicine monitoring network technology has become a hot research topic [1]. This technology allows doctors to remotely diagnose the condition of patients and provide timely medical advice. In the remote medical monitoring network, the transmission of local medical data, such as heartbeat, respiration, blood oxygen, and pulse, relies mainly on short-distance wireless communications technology such as Bluetooth, Wi-Fi, and ZigBee [2]. These short-distance wireless communications technologies have different applications and transmission rates. They have their own advantages and disadvantages, and each technology is constantly adapting to different types or standards of medical data transmission. The objective of our study is to design a multistandard receiver that can adapt to different communication standards so that various medical data can be flexibly received.

At present, short-distance wireless communications technologies for telemedicine monitoring, such as Bluetooth,

Wi-Fi, and ZigBee, all use the 2.4 GHz frequency range; therefore, spectrum resources are absent. Improving spectrum utilization is a very important problem in the receiver. To avoid aliasing caused by bandpass sampling (BPS), most researchers consider choosing the lowest possible sampling frequency in order to reduce the burden of subsequent digital processing without aliasing in the spectrum [3–5]. Many researchers have tried to find a new algorithm to simplify the frequency selection process [6–8]. However, preventing aliasing will reduce spectrum utilization and the complexity of the computation process will increase the difficulty of implementation.

This work proposes a solution for aliasing in receivers that can reduce the limitations in sampling frequency, improve spectrum utilization, and realize multistandard receivers. In previous work, a sampling frequency that is twice the signal bandwidth was used to receive two-band signals [9]. This method allowed two signals to overlap with each other and separate using interplants, which eases the restriction on sampling frequency. However, this method did not provide the constraint conditions for

FIGURE 1: Structure of telemedicine monitoring system.

FIGURE 2: Spectra after BPS.

sampling frequency and the solution for aliasing by more than two signals. Based on this method, this paper gives the constraint conditions for frequency selection and a method to process aliasing by more than two standard signals.

This paper is organized as follows. Section 2 gives the structure of telemedicine monitoring system and the method to design antialiasing filters to suppress aliasing. In Section 3, aliasing analysis and constraint conditions are given and analyzed. Section 4 presents the simulation results for the multistandard receiver and spectral analysis. Section 5 tests the proposed algorithm in hardware. Section 6 provides concluding remarks.

2. Multistandard Receiver

2.1. Structure of Telemedicine Monitoring System. The structure of telemedicine monitoring system is shown in Figure 1.

Medical data, such as heartbeat, respiration, blood oxygen, and pulse, are measured by different equipment and transmitted by different wireless communications technology. The multistandard receiver samples the signals and removes aliasing. The received data are sent to the medical gateway and transmitted to the remote client via the Internet.

The core of the system is the design of an antialiasing module that can separate the overlapped signals.

2.2. Antialiasing Filter Design. Assume that the primary signal is sampled at a sampling rate f_s . Any signal in the frequency zone of index n expressed as [9]

$$\left(n - \frac{1}{2}\right)f_s < |f| < \left(n + \frac{1}{2}\right)f_s \quad (1)$$

is aliased into the first Nyquist zone $|f| < f_s/2$, which is the frequency zone with index zero.

Assume that four different standard signals, S'_1, S'_2, S'_3 , and S'_4 , with frequency zone index n_1, n_2, n_3 , and n_4 , respectively, are bandpass sampled at sampling frequency f_s simultaneously. The sampled spectra are represented as S_1, S_2, S_3 , and S_4 , respectively, as shown in Figure 2, where signals S_1 and S_2 overlap in area 0 to f_1 , and signals S_3 and S_4 overlap in area f_1 to $f_s/2$.

In order to separate the overlapping signals, a second-order BPS sampling structure is designed, as shown in Figure 3. Two analog-to-digital converters (ADCs), ADC A and ADC B, are used for BPS, where ADC B introduces time delay T_Δ . The two sampled channels are referred to as channel A and channel B.

According to the characteristics of second-order BPS [4], the sampled signal spectra in the two channels satisfy the following equation:

$$S_{iB} = S_{iA} \cdot \beta^{-ni}, \quad (2)$$

where S_{iA} ($i = 1, 2, 3, 4$) represents the signals sampled in channel A, and S_{iB} represents the signals sampled in channel B, $\beta = e^{-j2\pi T_\Delta f_s}$. Because the negative and positive spectra are symmetrical, here, we discuss only the positive spectra.

In Figure 3, antialiasing filters F_{A1} and F_{B1} should be designed to suppress signals S_2 and S_4 , and F_{A2} and F_{B2} should suppress signals S_1 and S_3 .

In area 0 to f_1 , S_2 needs to be suppressed. Thus, in the frequency domain, F_{A1} and F_{B1} should satisfy

$$\begin{aligned} S_{1A}F_{A1} + S_{1B}F_{B1} &= S_{1A}, \\ S_{2A}F_{A1} + S_{2B}F_{B1} &= 0. \end{aligned} \quad (3)$$

FIGURE 3: Structure of the second-order BPS system.

After simplification,

$$\begin{aligned} F_{A1} + \beta^{-n1} F_{B1} &= 1, \\ F_{A1} + \beta^{-n2} F_{B1} &= 0. \end{aligned} \quad (4)$$

From (2) and (3), we get

$$\begin{aligned} F_{A1} &= \frac{-\beta^{-n2}}{\beta^{-n1} - \beta^{-n2}}, \\ F_{B1} &= \frac{1}{\beta^{-n1} - \beta^{-n2}}, \\ f &\in [0, f_1]. \end{aligned} \quad (5)$$

In area f_1 to $f_s/2$, S_4 needs to be suppressed. Thus, in the frequency domain, F_{A1} and F_{B1} should satisfy

$$\begin{aligned} S_{3A} F_{A1} + S_{3B} F_{B1} &= S_{3A}, \\ S_{4A} F_{A1} + S_{4B} F_{B1} &= 0. \end{aligned} \quad (6)$$

After simplification,

$$\begin{aligned} F_{A1} + \beta^{-n3} F_{B1} &= 1, \\ F_{A1} + \beta^{-n4} F_{B1} &= 0. \end{aligned} \quad (7)$$

From (2) and (7), we get

$$\begin{aligned} F_{A1} &= \frac{-\beta^{-n4}}{\beta^{-n3} - \beta^{-n4}}, \\ F_{B1} &= \frac{1}{\beta^{-n3} - \beta^{-n4}}, \\ f &\in \left[f_1, \frac{f_s}{2} \right]. \end{aligned} \quad (8)$$

FIGURE 4: The relationship between signal mirroring frequency and sampling frequency.

Using the same method, we can get the expressions for F_{A2} and F_{B2} in the frequency domain, as shown as follows:

$$\begin{aligned} F_{A2} &= \frac{-\beta^{-n1}}{\beta^{-n2} - \beta^{-n1}}, \\ F_{B2} &= \frac{1}{\beta^{-n2} - \beta^{-n1}}, \\ f &\in [0, f_1], \\ F_{A2} &= \frac{-\beta^{-n3}}{\beta^{-n4} - \beta^{-n3}}, \\ F_{B2} &= \frac{1}{\beta^{-n4} - \beta^{-n3}}, \\ f &\in \left[f_1, \frac{f_s}{2} \right]. \end{aligned} \quad (9)$$

3. Constraint Conditions

3.1. Aliasing Analysis. Assume an RF signal with central frequency f_c bandpass sampled at sampling frequency f_s , the central frequency in the first Nyquist zone (called mirroring frequency) can be defined as

$$f_{AF} = \begin{cases} f_c - \frac{rf_s}{2}, & r = \left\lfloor \frac{f_c}{f_s/2} \right\rfloor \text{ is even,} \\ \frac{(r+1)f_s}{2} - f_c, & r = \left\lfloor \frac{f_c}{f_s/2} \right\rfloor \text{ is odd.} \end{cases} \quad (10)$$

where $\lfloor \bullet \rfloor$ means to round down.

Assume three bandpass signals that are received simultaneously with mirroring frequency f_{AF1} , f_{AF2} , and f_{AF3} .

FIGURE 5: (a) Aliasing diagram (Case a). (b) Aliasing diagram (Case b). (c) Aliasing diagram (Case c).

TABLE 1: Parameters of four input signals.

Number	Central frequency	Signal types	Frequency zone index	Frequency offset
S_1	2.428 GHz	Bluetooth	101	4 MHz
S_2	2.452 GHz	Wi-Fi	102	4 MHz
S_3	2.408 GHz	ZigBee	100	8 MHz
S_4	2.464 GHz	Bluetooth	103	8 MHz

Figure 4 shows the relationship between the mirroring frequency and sampling frequency f_s .

Consider signal f_{AF2} , with different selections of f_s , it has four kinds of aliasing:

- (i) Aliasing by self-image spectrum around zero frequency, as shown in area A of Figure 4
- (ii) Aliasing by self-image spectrum around $f_s/2$ frequency, as shown in area B of Figure 4
- (iii) Aliasing by another signal, as shown in area C of Figure 4
- (iv) Aliasing by another two signals, as shown in area D of Figure 4

The traditional way of selecting f_s is to avoid all kinds of aliasing, which limits the area of f_s , and usually needs a large amount of calculations. In Section 2, aliasing caused by image spectrum and overlap with two signals can be solved by software. Hence, when we select f_s , less limiting conditions are allowed.

3.2. Constraint Condition. According to the abovementioned rules, the sampling rate constraint conditions are

FIGURE 6: Signal spectra after BPS.

given to allow the presence of two aliasing signals at the same location after sampling. The details can be expressed by the following equations:

$$f_s \geq 2[B_{\max} + 2B_G]. \quad (11)$$

If

$$f_{DFi} < \frac{B}{2 + B_G}, \quad (12)$$

then

$$\frac{B_j}{2 + B_G} < f_{DFj}. \quad (13)$$

FIGURE 7: Signal spectra after antialiasing filters F_{A1} and F_{B1} . FIGURE 8: Signal spectra after antialiasing filters F_{A2} and F_{B2} .

If

$$f_{DFi} > \frac{f_s}{2} - \left(\frac{B_i}{2 + B_G} \right), \quad (14)$$

then

$$f_{DFj} < \frac{f_s}{2} - \left(\frac{B_j}{2 + B_G} \right), \quad (15)$$

where $i = 2, 3, \dots, N$ and $j = 2, 3, \dots, i - 1$.

If $f_{AFli} > f_{AFlj}$, then $f_{AFhk} < f_{AFli}$ or $f_{AFlk} > f_{AFhi}$; if $f_{AFli} < f_{AFlj}$ and $f_{AFhi} > f_{AFhj}$, then $f_{AFhk} < f_{AFlj}$ or $f_{AFlk} > f_{AFhj}$; if $f_{AFli} < f_{AFlj}$ and $f_{AFli} < f_{AFhi} < f_{AFhj}$, then $f_{AFlk} < f_{AFlj}$ or $f_{AFlk} > f_{AFhi}$, where $i = 2, 3, \dots, N$, $j = 1, 2, 3, \dots, i - 1$, $k \in [1, N]$, $k \neq i$, and $k \neq j$.

In the above constraint conditions, $B_{\max}$ represents the maximum bandwidth of N bandpass signals; B_G represents protection bandwidth; B_i , f_{DFi} , f_{AFli} , and f_{AFhi} represent the bandwidth, central frequency, minimum frequency, and maximum frequency of signal i , respectively, in the first Nyquist region after BPS.

Constraint 1. It indicates that the sampling frequency needs to be two times greater than the maximum bandwidth of the signal (plus protection bandwidth).

Constraint 2. It means that only one signal is allowed to have zero-bound aliasing or $f_s/2$ -bound aliasing, that is, the spectral aliasing of the image itself.

Constraint 3. It means that only two aliasing signals are allowed in the same location. There are three cases for this constraint. Case a $f_{AFli} > f_{AFlj}$ is shown in Figure 5(a). Case b $f_{AFli} < f_{AFlj}$ and $f_{AFhi} > f_{AFhj}$ is shown in Figure 5(b). Case c $f_{AFli} < f_{AFlj}$ and $f_{AFli} < f_{AFhi} < f_{AFhj}$ is shown in Figure 5(c).

4. Simulation Results for Multistandard Receiver

Taking four input signals as examples, the parameters are shown in Table 1. The sampling frequency is 24 MHz. Time delay between two sampling channels is 1200 ps.

FIGURE 9: Structure of test platform.

After BPS, signals S_1 and S_2 overlap at around 4 MHz, and signals S_3 and S_4 overlap at around 8 MHz, as shown in Figure 6.

After applying the antialiasing filters designed in Section 2, the overlapping signals can be separated. In Figure 7, S_2 and S_4 are suppressed, and only S_1 and S_3 are left. In Figure 8, S_1 and S_3 are suppressed, and S_2 and S_4 are left. The suppressed effects are more than 30 dB.

Using further low-pass or high-pass filter design, the four signals can be separated.

5. Hardware Test

5.1. Platform Design. In order to test in a real environment, hardware platform is designed using the structure as shown in Figure 9.

Signal generator is used to generate input RF signals. Two ADS5463 ADCs are used to realize second-order BPS. LMK03002C clock generator contributes time delay to ADC B. Antifilters are implemented in FPGA. Digital down conversion also should be implemented in FPGA. Low speed digital signals are transmitted to PC and received by GNU Radio.

5.2. Time Delay Compensation. According to (2), the theoretical phase difference between two ADC outputs can be described as

$$\theta_t = 2\pi n T_{\Delta} f_s \quad (16)$$

Considering the time delay error caused by hardware, practical phase difference can be written as

$$\theta_r = 2\pi n (T_{\Delta} + T') f_s + 2\pi (T_{\Delta} + T') f \quad (17)$$

where T' is time error which can be estimated by fitting the measured data. f is the frequency offset. $2\pi(T_{\Delta} + T')f$ denotes the compensation for group delay. In real environment, (17) is used to design antialiasing filters.

5.3. Test Results. Taking three input signals as examples, the parameters are shown in Table 2. The sampling frequency is 24 MHz. Theoretical time delay between two sampling channels is 1200 ps, that is, clock generate is

TABLE 2: Parameters of three input signals.

Number	Central frequency (GHz)	Signal types	Zone index	Frequency offset (MHz)	Down sampled by 2.5 (MHz)
S_{1r}	2.4275	Bluetooth	101	3.5	3.5
S_{2r}	2.450	Wi-Fi	102	2	2
S_{3r}	2.4106	ZigBee	100	10.6	1

set with delay 1200 ps. By fitting the measured data, time delay error can be estimated as $T' \approx 129$ ps. Then, time delay 1329 ps is used to design antialiasing filters in FPGA.

After BPS, three signals lies in 3.5 MHz, 2 MHz, and 10.6 MHz, respectively. To decrease the signal speed, signals are down sampled by 2.5, that is, signals send to PC with a sampling rate of 9.6 MHz. After down sampled, three signal lies in 3.5 MHz, 2 MHz, and 1 MHz, respectively. S_{2r} and S_{3r} are too closed to separate, so we design antialiasing filters to separate them. After applying the antialiasing filters designed in FPGA, S_{2r} and S_{3r} can be separated in channel one and channel two. In Figure 10, S_{2r} is suppressed, and only S_{3r} and S_{1r} are left. In Figure 11, S_{3r} is suppressed, and S_{2r} and S_{1r} are left.

6. Conclusions

Antialiasing filters were designed to separate more than two aliasing signals. The test results show that the antialiasing filters can suppress more than 30 dB. Based on this method, constraint conditions for selecting sampling rates are given. The algorithm is proven to be correct by hardware analysis. Compared with existing receivers in telemedicine monitoring systems, the proposed structure can solve the problem of aliasing and realize a multistandard receiver that can receive different standard signals simultaneously. This receiver can significantly improve spectrum utilization as well as the flexibility of receivers for telemedicine monitoring systems.

FIGURE 10: Signal spectra received by GNU Radio (channel one).

FIGURE 11: Signal spectra received by GNU Radio (channel two).

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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