STUDY ON A MULTIPLE SIGNAL RECEIVER USING UNDERSAMPLING SCHEME

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ABSTRACT

Making use of multiple communication services is desired at mobile terminals for various applications. Software Defined Radio (SDR) technology is the focus of much attention to realize such terminals [1], [2]. Multi-band and multi-signal receivers are investigated to realize such terminals. Undersampling is a potential method for simultaneous receiving of multi-band and multiple signals by selecting suitable sampling frequency. However, the sampling frequency becomes higher when receiving the signal of a communication system that occupies a wide bandwidth. This paper presents a novel sampling frequency selection scheme that enables selection of a lower sampling frequency by receiving at least the desired transmission channels in the wireless system signals.

1. INTRODUCTION

In SDR-based terminals, the signal processing normally executed by hardware such as an ASIC (Application Specific IC) or a custom IC is processed by software using DSP, FPGA or other reconfigurable processors. To extend the digital processing area and render the terminal applicable to many communication systems, it is desirable to set the ADC nearer the antenna part in receiver block diagrams. In normal baseband sampling receivers, some analog devices such as oscillators, mixers or filters restrict the flexibility of the receiver, because the parameters or values targeting a specific system are fixed and cannot be changed in such devices. To make a receiver more flexible, it is desirable to sample and digitize the received radio frequency signal at the RF frequency. The RF sampling scheme expands the region of the digital signal processing, and makes the receiver more programmable. However, a high speed ADC is required for the RF sampling receiver because the ADC needs to sample the high frequency signal and convert it to a digital signal. As a potential solution, we consider the undersampling scheme, in which the frequency conversion and sampling are performed simultaneously using a sampling frequency less than the Nyquist frequency of the sampled signal [3]-[5]. In the reference [3], the computational method for a sampling frequency of RF undersampling was proposed to sample and receive the signals of multiple communication systems simultaneously using single ADC. The paper presents the conditions needed to avoid the influences of interference from the aliasing signal of the other systems. Using the proposed schemes, individual channels from multiple communication systems can be received by one ADC. However, the sampling frequency becomes higher when receiving the signal of a communication system that occupies a wide bandwidth.

In this paper, a new frequency selection scheme is proposed to solve the aforementioned problem, which also avoids interference with a desired transmitting channel. The scheme offers a sampling frequency selection method according to the bandwidth of a transmitting channel, and not heavily dependent on system bandwidth. As a result, the sampling frequency becomes lower. The effect of the decrease in sampling frequency is evaluated by quantitative analysis.

2. UNDERSAMPLING [3]-[5]

Undersampling is a sampling technique that utilizes the aliasing signal caused by using a sampling frequency lower than the Nyquist frequency and where the signal is sampled and simultaneously converted to low frequency. Figure 1 shows an example of a block diagram of an RF sampling receiver. The signal received at the antenna is amplified by the LNA (Low Noise Amplifier). Thereafter, only the desired signal is passed by the BPF (Band Pass Filter). Using an appropriate sampling frequency F_S, the desired signal is frequency-converted to a frequency range between 0 and $F_S/2$. Out-band interference and noises not rejected by the BPF are also frequency-converted to the same frequency range. Thus, the signal can be frequency-converted without an oscillator or a mixer by undersampling. Here, the relation between the desired signal's center frequency F_C and the frequency-converted signal's center frequency F_{IF} is indicated by Eq. (1).

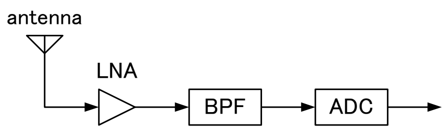
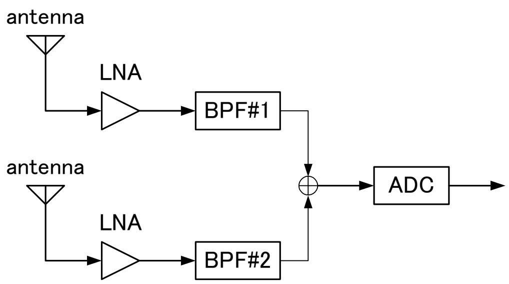
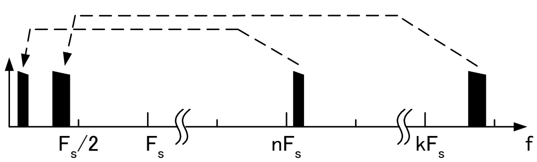


Fig. 1 Block diagram of RF sampling receiver.



(a) Receiver structure for undersampling multiple system signals.



(b) Conceptual view of spectrum.

Fig. 2 Undersampling for multiple system signals.

$$\text{if}\ \ \text{fix}\left(\frac{F_C}{\frac{F_S}{2}}\right)\ \text{is}\ \begin{cases}\text{even}, & F_{IF} = \text{rem}(F_C, F_S)\\ \text{odd}, & F_{IF} = F_S - \text{rem}(F_C, F_S)\end{cases} \tag{1}$$

In Eq. (1), fix (a) is a function used to obtain the value after omitting the decimal places of the value a, and rem (a, b) is a function to obtain the remainder of the value a divided by the value b. The center frequency of the signal after frequency-conversion by undersampling is obtained by Eq. (1). An appropriate sampling frequency by which the entire bandwidth of the desired wireless system is converted to a frequency range between 0 and $F_S/2$, should be selected to avoid interference from the aliasing signal of the desired system. Such a sampling frequency F_S and the frequency-converted signal's center frequency F_{IF} are required to satisfy both Eqs. (2) and (3).

$$0 < F_{IF} - \frac{BW}{2} \tag{2}$$

$$F_{IF} + \frac{BW}{2} < \frac{F_S}{2} \tag{3}$$

In Eqs. (2) and (3), BW indicates the bandwidth of the desired system. The undersampling scheme is applicable when the sampling frequency F_S satisfying Eqs. (2) and (3) exists.

To sample the signals of multiple systems simultaneously using a single ADC, the signals must be pre-bandpass filtered, and the frequency bandwidths of the signals restricted. As an example, the structure of a receiver in which the signals of multiple systems are sampled simultaneously is shown in Fig. 2, as well as a conceptual view of the spectrum.

First, the center frequency of each system after the frequency-conversion is calculated by Eq. (1). Then the sampling frequency, by which the signals of each system avoid interferences from the system itself, is selected by finding the value satisfying Eqs. (2) and (3). A condition should be added to sample the signals of multiple systems simultaneously, and the sampling frequency is selected. Equation (4) is the condition to sample the signals of two systems without mutual interference.

$$\left|F_{IF_1} - F_{IF_2}\right| \geq \frac{BW_1 + BW_2}{2} \tag{4}$$

The subscript in Eq. (4) is the number identifying the two systems. For example, F_{IF1} indicates the frequency-converted center frequency of System-1. Similarly, BW_1 indicates the bandwidth of System-1. Equation (4) can be expanded to be applicable for N systems. Equation (5) is the condition to sample the signals of N systems by single ADC simultaneously.

$$\left|F_{IF_b} - F_{IF_a}\right| \geq \frac{BW_b + BW_a}{2} \qquad \begin{cases} a=2, \cdots, N \\ b=1, \cdots, a-1 \end{cases} \tag{5}$$

The subscripts a and b in Eq. (5) identify the systems' number. By applying Eqs. (1)-(3) and (5), the sampling frequency that can be used to sample the signals of N systems is selected.

3. PROPOSED SCHEME

In the previous chapter, a sampling frequency selection scheme to sample the signals of multiple systems simultaneously was shown. The signals of entire multiple systems can be sampled using such a scheme without being subject to the influence of the aliasing image. However, sampling the signals using the sampling frequency over twice the sum of all systems' bandwidths is required to satisfy Nyquist's sampling theorem. Therefore, the scheme has a problem in that the sampling frequency becomes high

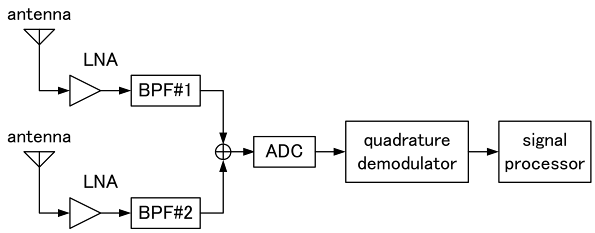


Fig. 3 System model.

Table 1 Parameters of systems.

	System 1	System 2
Carrier Frequency F_C [MHz]	2122.5	1906.55
System Bandwidth BW [MHz]	13.75	26.1
Channel Bandwidth BW_{ch} [MHz]	1.25	0.3

when the bandwidth of any receiving system is wide or the receiving of many systems is desired. In this chapter, we propose a new sampling frequency selection scheme by which a lower sampling frequency can be selected, and with the aim of receiving only the desired channels of each system.

3.1. Sampling frequency selection scheme to receive signal of desired channel

F_{IF} and F_{IFch}, the center frequencies of a system and a desired channel after frequency-conversion respectively, are settled by Eqs. (1) and (6).

$$\text{if } \mathrm{fix}\left(\frac{F_{ch}}{\frac{F_S}{2}}\right) \text{ is } \begin{cases} \text{even}, & F_{IF_{ch}} = \mathrm{rem}(F_{ch}, F_S) \\ \text{odd}, & F_{IF_{ch}} = F_S - \mathrm{rem}(F_{ch}, F_S) \end{cases} \quad (6)$$

In Eq. (6), F_{ch} indicates the center frequency of the desired channel before frequency-conversion. The center frequency of a desired channel is revealed by Eq. (6). In order to receive and demodulate the signal of the desired channel, the frequency-converted signal of the desired channel must not be influenced by any aliasing signals. Therefore, it is necessary to select a sampling frequency satisfying Eqs. (7) and (8).

$$F_{IF_{ch}} - \frac{BW_{ch}}{2} > -\left(F_{IF} - \frac{BW}{2}\right) \quad (7)$$

$$\frac{F_S}{2} - \left(F_{IF_{ch}} + \frac{BW_{ch}}{2}\right) > \left(F_{IF} + \frac{BW}{2}\right) - \frac{F_S}{2} \quad (8)$$

In Eqs. (7) and (8), BW_{ch} indicates the bandwidth of the desired channel. Using a sampling frequency satisfying Eqs. (7) and (8), the signal of the desired channel is received without being subject to the influence of the aliasing image.

3.2. Sampling frequency selection scheme for multiple systems

In addition to the constraint of the sampling frequency described in Section 3.1, it is necessary to select a sampling frequency by which the frequency-converted signals of each desired channel are not influenced by the aliasing signals of other systems, to receive and demodulate every signal of each desired channel. Here is an example of receiving each signal of two channels in two systems. Firstly, select the sampling frequency by which each system and each desired channel satisfy Eqs. (1) and (6)-(8). Then pick up the sampling frequency by which the signals of each desired channel are not influenced by the signals of the aliasing images of other systems, using Eqs. (9) and (10).

$$\left|F_{IF_{ch_2}} - F_{IF_1}\right| \geq \frac{BW_{ch_2} + BW_1}{2} \quad (9)$$

$$\left|F_{IF_2} - F_{IF_{ch_1}}\right| \geq \frac{BW_2 + BW_{ch_1}}{2} \quad (10)$$

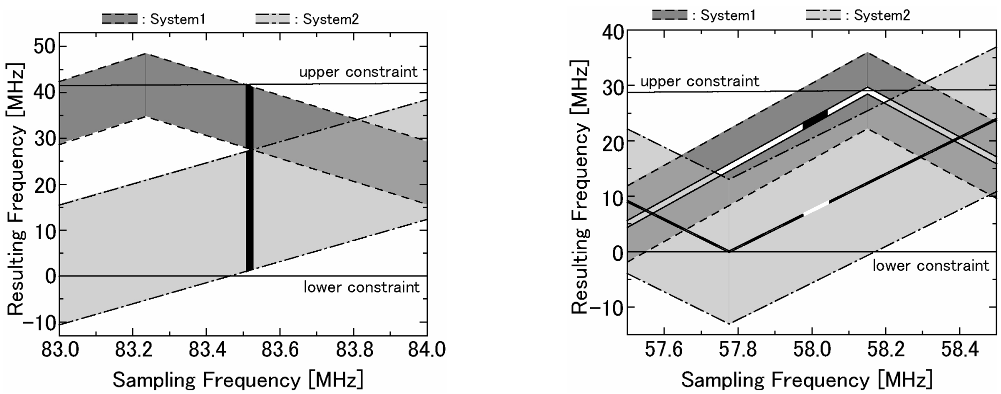
By the sampling frequency satisfying both Eqs. (9) and (10), the signals of the desired channels in each system can be undersampled without being subject to the influence of the signals caused from another system.

Equations (9) and (10) can be generalized into Eq. (11). Equation (11) can then be used to decide the sampling frequency to receive the signals of N desired channels in N pairs of wireless systems.

$$\left|F_{IF_b} - F_{IF_{ch_a}}\right| \geq \frac{BW_b + BW_{ch_a}}{2} \quad \begin{cases} a = 1, \cdots, N \\ b = 1, \cdots, N \\ a \neq b \end{cases} \quad (11)$$

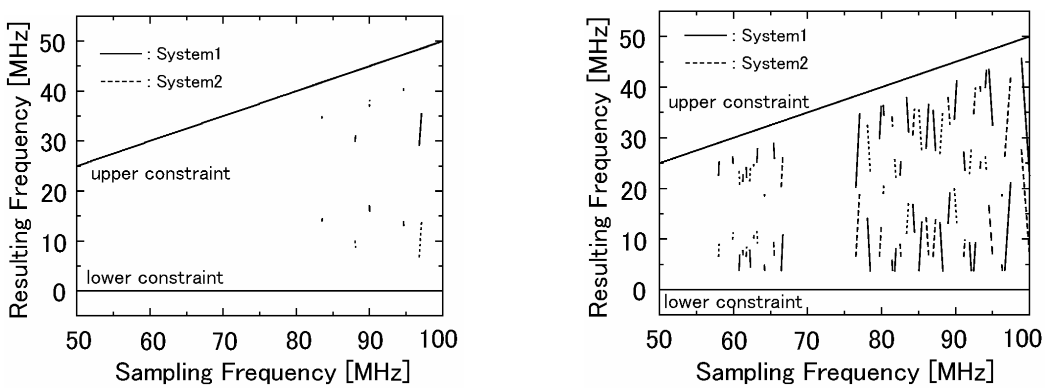
4. QUANTITATIVE ANALYSIS

In this chapter, the frequency selection schemes for receiving an entire system's signals and the desired channels' signals in the systems by undersampling, are compared. Moreover, the effect of decreasing the sampling frequency is evaluated quantitatively.



(a) Conventional. (b) Proposed.

Fig. 4 Relation between sampling frequency and frequency after frequency-conversion. (Near minimum sampling frequency)



(a) Conventional. (b) Proposed.

Fig. 5 Relation between sampling frequency and frequency after frequency-conversion. (Sampling frequency between 100MHz and 50MHz)

4.1. System model

The system model used to evaluate the sampling frequency selection scheme is shown in Fig. 3. After the signals received at each antenna are amplified by LNA, the outband signal is suppressed by BPF. The bandwidth restricted signals are mixed and undersampled by an ADC simultaneously, following which the signals of the desired channels are demodulated by each demodulation processing. Here, the characteristics in the case of receiving two systems' signals are assumed and evaluated. Table 1 shows the parameters of the two systems used in the evaluation. System 1 with a center frequency of 2122.5 MHz and System 2 with a center frequency of 1906.55 MHz are used. System 1 has eleven channels over a frequency of 2116.25 MHz with 1.25 MHz channelization. System 2 has 87 channels over a frequency of 1893.65 MHz with 0.3 MHz channelization.

Note that in the proposed scheme, the sampling frequency should be variable to sample the signals of any channel combination in each system.

4.2. Sampling frequency to sample signals of two desired systems (Conventional scheme)

Figure 4 (a) shows the relation between the sampling frequency and that of the desired systems after frequency-conversion in the case of receiving entire systems' signals. In Fig. 4 (a), the horizontal axis indicates the sampling frequency, and the vertical axis indicates that after frequency-conversion. For example, by undersampling the signal using a sampling frequency of 83.0 MHz, System 1 is converted to a frequency range of between 28.6 MHz and 42.4 MHz, and System 2 is converted to one between -10.7 MHz and 15.5 MHz. If the frequency after frequency-conversion exceeds the upper constraint ($F_S/2$) or is below the lower constraint (0), the aliasing signal of the system itself becomes significant. Therefore, in the case of a sampling frequency of 83.0 MHz, part of the signal of System 1 beyond 41.5 MHz turns back and consequently, at a frequency of over 40.6 MHz (= 41.5-(42.4-41.5)), the signal is subject to the influence of its own signal. Similarly, part of the signal of System 2 below 0 MHz turns back. At a frequency of below 10.7 MHz (= 0 - (-10.7)) the signal is subject to the influence of the signal of the self system.

Hence, the frequency-converted signals of each system must exist in the frequency range between the upper and lower constraints and be non-overlapping, to receive two entire systems' signals and avoiding the influence of the aliasing signals of the self-system or another system. In Fig. 4 (a), the regions of the sampling frequency and that after frequency-converting the systems, satisfying the aforementioned conditions, are indicated in gray. The minimum sampling frequency for undersampling is around 83.5 MHz from Fig. 4 (a).

4.3. Sampling frequency to sample signals of desired channels in two systems (Proposed scheme)

Figure 4 (b) shows the relation between the sampling frequency and the frequency of desired systems after frequency-conversion when receiving the signals of the desired channels in two systems. Here, the two desired channels are assumed to be the center channels of the systems, and are indicated by solid lines in Fig. 4 (b).

The signals of the desired channels must not overlap with those of the self-system or other system in the frequency domain. Figure 4 (b) indicates the minimum sampling frequency satisfying this condition to be around 58.0 MHz. Thus the proposed scheme decreases the minimum sampling frequency.

Figure 5 shows the relation between the sampling frequency and the frequency of Systems 1 and 2 after frequency-conversion. Figure 5 (a) shows the center frequency of two desired systems when receiving the entire systems' signals, while Fig. 5 (b) shows the center frequency of two desired channels; when receiving the signals of the desired channels in two systems. For example, Fig. 5 (a) indicates only around 83.5 MHz may be used for the sampling frequency of undersampling in a frequency range from 80.0 MHz to 85.0 MHz, and the center frequencies of Systems 1 and 2 are frequency-converted to 35.0 MHz and 15.0 MHz, respectively. By comparing Figs. 5 (a) and (b), the proposed scheme can increase the number of sampling frequencies available for undersampling between 80 MHz and 100 MHz.

5. CONCLUSION

This paper describes a new sampling frequency selection scheme to undersample the signals of multiple systems in different frequency bands, simultaneously. While the scheme requires variable-rate compatible ADCs circuits, it effectively decreases the sampling frequency. Consequently power consumption at the digital signal processing can be reduced by the lower sampling frequency. This scheme is particularly effective in future broadband wireless systems where the system bandwidth widens and multiple communication systems are used cooperatively.

6. REFERENCES

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