A New Architecture of Matched Filter for Chirp Spread Spectrum in IEEE 802.15.4a

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We propose a new matched filter architecture for chirp spread spectrum in IEEE 802.15.4a. By using relations among the four subchirps, the proposed architecture comprises four subfilters utilizing only a set of coefficients matched to the first subchirp. The four subfilters share adders and registers, and as a result, the required adders and registers for implementation are reduced.

Keywords: Chirp spread spectrum (CSS), implementation, hardware architecture, hardware complexity, matched filter.

I. Introduction

Chirp spread spectrum (CSS) is a physical layer standard of IEEE 802.15.4a whose objectives are high-precision ranging and low-rate data communication with low hardware complexity [1]. For high decoding performance and robust time and frequency synchronization, a matched filter is necessary for CSS [2]-[4].

Since a symbol of CSS is composed of four subchirps [1], four subfilters whose coefficients are matched to the four subchirps are needed in CSS. As shown in [5], a complex FIR filter is implemented by three real FIR filters. Then, twelve real FIR filters are required in CSS. Eventually, hardware complexity becomes a critical issue. To lower the hardware complexity, a new matched filter architecture is proposed.

II. Relations among the Four Subchirps of CSS

In this section, we examine relations among the four subchirps. For convenience, we explain the relations of subchirps based on simultaneously operating piconet (SOP) 1 [1].

As in [1], four digitized subchirps of CSS at the baseband are presented by

$$s_{k,n} = \exp\left[j\left(\omega_k n + \xi_k \left(\mu/2\right) n^2\right)\right] \cdot P_n, \tag{1}$$

where k denotes the subchirp index (k=0, 1, 2 and 3), and n denotes a sample index, where $|n| \le (1/2) \lfloor T_{\text{sub}}/T_s \rfloor$ Here, $\lfloor x \rfloor$ is the largest integer smaller or equal to x; $s_{k,n}$ denotes the n-th sample of the k-th subchirp; T_{sub} denotes the time duration of a subchirp; T_s is sampling duration; $j = \sqrt{-1}$; ω_k denotes the center frequency of the k-th subchirp; and ξ_k is a numerical parameter for subchirp directions. The constant μ denotes the characteristics of the subchirp, and P_n is a raised cosine window.

We investigate the relation between subchirps 0 and 1 in SOP 1. The raised cosine window P_n is bisymmetry, and ω_1 has the same value $-\omega_0$ as in [1]. Then, subchirp 1 is expressed by the reverse indexed subchirp 0 as

$$\begin{aligned} s_{1,n} &= \exp\left[j\left\{\omega_1 n + \left(\mu/2\right) n^2\right\}\right] \cdot P_n \\ &= \exp\left[j\left\{\omega_0 (-n) + \left(\mu/2\right) (-n)^2\right\}\right] \cdot P_{-n} = s_{0,-n}. \end{aligned} \tag{2}$$

Using a similar process, subchirps 2 and 3 are expressed by the conjugate subchirp 0 in (3) and the conjugate and reverse indexed subchirp 0 in (4), respectively:

$$\begin{aligned} s_{2,n} &= \exp\left[j\left\{\omega_2 n - \left(\mu/2\right) n^2\right\}\right] \cdot P_n \\ &= \exp\left[-j\left\{\omega_0 n + \left(\mu/2\right) n^2\right\}\right] \cdot P_n = s_{0,n}^{*}, \end{aligned} \tag{3}$$

$$\begin{aligned} s_{3,n} &= \exp\left[j\left\{\omega_3 n - \left(\mu/2\right) n^2\right\}\right] \cdot P_n \\ &= \exp\left[-j\left\{\omega_0 (-n) + \left(\mu/2\right) (-n)^2\right\}\right] \cdot P_{-n} = s_{0,-n}^{*}. \end{aligned} \tag{4}$$

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III. Proposed Architecture of the Matched Filter

Since the four subfilters of CSS are complex filters, the real and imaginary parts should be considered separately. Real and imaginary output sequences of subfilter 0 are expressed as

$$y^r_{0,n} = \sum_{l=-(1/2)N_{\text{sub}}}^{(1/2)N_{\text{sub}}} x^r_{n-l} s^r_{0,l} - \sum_{l=-(1/2)N_{\text{sub}}}^{(1/2)N_{\text{sub}}} x^i_{n-l} s^i_{0,l}, \text{ and}$$

$$y^i_{0,n} = \sum_{l=-(1/2)N_{\text{sub}}}^{(1/2)N_{\text{sub}}} x^r_{n-l} s^i_{0,l} + \sum_{l=-(1/2)N_{\text{sub}}}^{(1/2)N_{\text{sub}}} x^i_{n-l} s^r_{0,l}, \quad (5)$$

where $\{\}^r$ denotes the real part of $\{\}$, and $\{\}^i$ denotes the imaginary part of $\{\}$; $y^r_{0,n}$ is the n-th real output sequence of the subfilter 0; x^r_n is the n-th real input sequence; $s^r_{0,n}$ is the n-th real coefficient that is matched to the n-th real sample of the subchirp 0; and N_{sub} is the number of coefficients in the subfilter.

The coefficients of the subfilters 1, 2, and 3 are replaced by those of the subfilter 0 by using the relations among the subchirps described in the previous section. As a result, the four subfilters are designed by utilizing only the coefficients that are matched to subchirp 0. The output sequences of subfilters 1, 2, and 3 are given as

$$y^r_{1,n} = \sum_{l=-(1/2)N_{\text{sub}}}^{(1/2)N_{\text{sub}}} x^r_{n-l} s^r_{0,-l} - \sum_{l=-(1/2)N_{\text{sub}}}^{(1/2)N_{\text{sub}}} x^i_{n-l} s^i_{0,-l},$$

$$y^i_{1,n} = \sum_{l=-(1/2)N_{\text{sub}}}^{(1/2)N_{\text{sub}}} x^r_{n-l} s^i_{0,-l} + \sum_{l=-(1/2)N_{\text{sub}}}^{(1/2)N_{\text{sub}}} x^i_{n-l} s^r_{0,-l},$$

$$y^r_{2,n} = \sum_{l=-(1/2)N_{\text{sub}}}^{(1/2)N_{\text{sub}}} x^r_{n-l} s^r_{0,l} + \sum_{l=-(1/2)N_{\text{sub}}}^{(1/2)N_{\text{sub}}} x^i_{n-l} s^i_{0,l},$$

$$y^i_{2,n} = \sum_{l=-(1/2)N_{\text{sub}}}^{(1/2)N_{\text{sub}}} x^r_{n-l} s^i_{0,l} - \sum_{l=-(1/2)N_{\text{sub}}}^{(1/2)N_{\text{sub}}} x^i_{n-l} s^r_{0,l},$$

$$y^r_{3,n} = \sum_{l=-(1/2)N_{\text{sub}}}^{(1/2)N_{\text{sub}}} x^r_{n-l} s^r_{0,-l} + \sum_{l=-(1/2)N_{\text{sub}}}^{(1/2)N_{\text{sub}}} x^i_{n-k} s^i_{0,-l}, \text{ and}$$

$$y^i_{3,n} = \sum_{l=-(1/2)N_{\text{sub}}}^{(1/2)N_{\text{sub}}} x^r_{n-l} s^i_{0,-l} - \sum_{l=-(1/2)N_{\text{sub}}}^{(1/2)N_{\text{sub}}} x^i_{n-l} s^r_{0,-l}. \quad (6)$$

The proposed matched filter is based on a transposed form, which is composed of two parts: a multiplier block (MB) and a register and adder block (RAB). In the transposed form, the hardware complexity of the MB is reduced [6]-[8] because of the property that all multiplications are products of a single input multiplicand.

Figure 1 shows the proposed architecture of the matched filter for CSS. The MBs, which are composed of the coefficients matched to subchirp 0, are shared by the four subfilters. For real and imaginary input sequences, there are two MBs composed of adders and shifters [8]. Subfilters 0 and 2 share RABs because of the conjugate relation between subchirps 0 and 2. Eventually, the outputs of subfilters 0 and 2 are determined by the adders or subtractors that add or subtract the outputs of shared RABs. Subfilters 1 and 3 also have the same relations. In subfilters 1 and 3, reverse blocks change the order of input sequences to generate the reverse indexed coefficients. RABs accumulate the output sequences of reverse blocks.

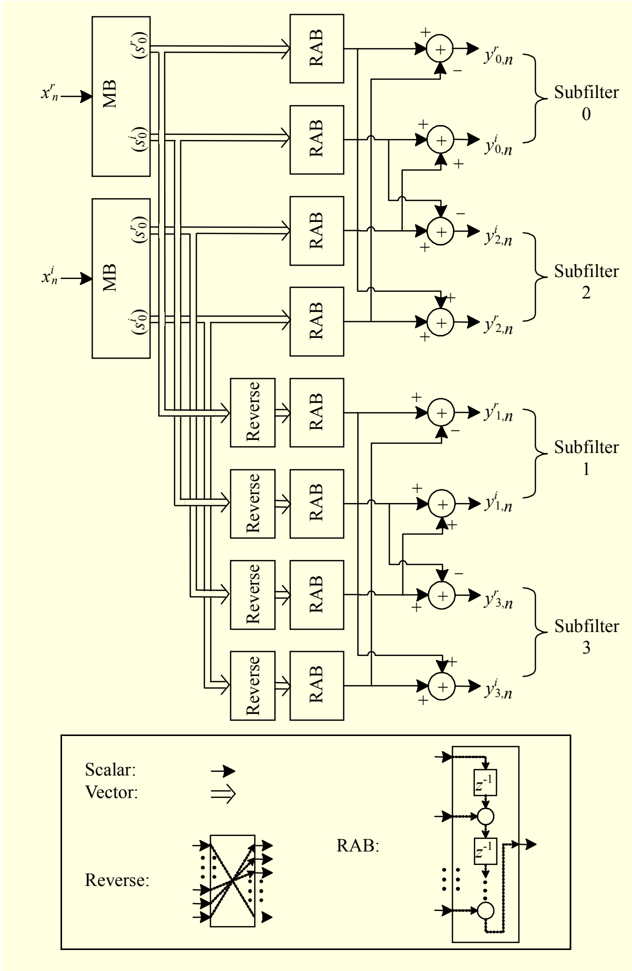

Fig. 1. Structure of the proposed CSS matched filter.

IV. Implementation Results

We compared the hardware complexity of the proposed architecture with that of conventional architecture in [5] based on the number of used adders and registers for implementation.

Figure 2 shows the number of adders required to implement MBs with the change of quantization bits in the proposed and conventional architectures. In this simulation, we assumed that the sampling frequency is 32 MHz and the filter tap size is 38. MBs are designed by using the n-dimensional reduced adder graph algorithm [8]. The proposed architecture needs MBs composed of only a set of coefficients matched to the first subchirp while the conventional one needs MBs composed of the coefficients matched to the four subchirps. As a result, the

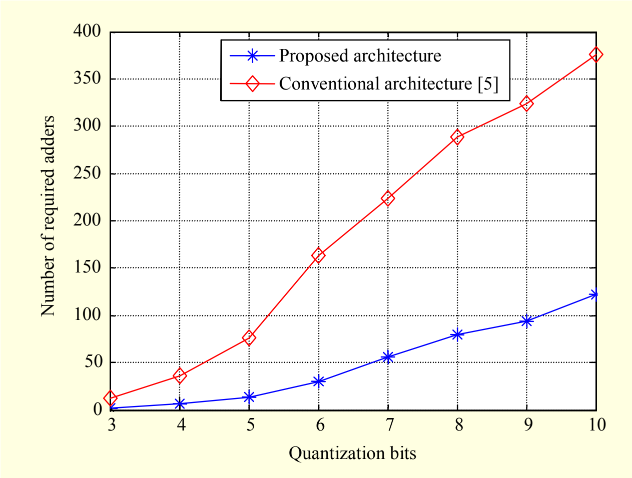

Fig. 2. Numbers of adders required to implement MBs.

Table 1. Comparison results of required adders and registers.

	Adders	Registers
Proposed architecture	8 (N)	8 (N–1)
Conventional architecture [4]	12 (N)	12 (N–1)

Table 2. Characteristics of the CSS MODEM chip.

Chip size	25×25 mm^2	Maximum clock rate	67.3 MHz
Total pins	208	I/O pins	181
I/O supply	3.3 V	Core supply	1.8 V

proposed architecture reduces the number of required adders by nearly 75%.

The numbers of adders and registers required for the proposed and conventional architectures except MBs are listed in Table 1, where N denotes the filter tap size of a subfilter.

An RAB consists of N–1 adders and registers. Three RABs are required for a complex FIR filter [5]. Eventually, twelve RABs are required for the conventional architecture since the four subfilters are required for CSS. Eight RABs, however, are required for the proposed architecture since subfilters 0 and 2 and subfilters 1 and 3 can share RABs. Both the proposed and conventional architecture require eight adders to add the outputs of RABs. The conventional architecture needs four more adders to make the inputs of MBs. As a result, the number of required adders and registers for the proposed architecture is reduced by 33.3%.

A CSS modulator and demodulator (MODEM), which includes the proposed matched filter, was modeled using Verilog hardware description language and implemented in very large scale integration with a cell library based on

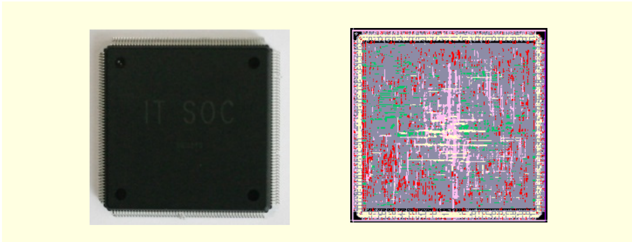

Fig. 3. CSS MODEM chip and its layout results.

Chartered 0.18 μm 1-poly, 5 metal complementary metal oxide semiconductor technology. Here, 3,268 cells were utilized for the CSS MODEM chip, and 874 cells were utilized for the proposed matched filter. The function of the CSS MODEM chip was verified by comparing simulated waveforms with measured wave-forms. Table 2 shows the characteristics of the designed CSS MODEM chip, and Fig. 3 shows the CSS MODEM chip and its layout.

V. Conclusion

A novel matched filter architecture for CSS was proposed and implemented. The proposed architecture reduced the number of required adders and registers compared with the conventional one. The proposed architecture could be applied to CSS systems with low hardware complexity.

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