Orthogonal Frequency Coding for SAW Device Applications

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Abstract- This paper presents the concept of orthogonal frequency coding (OFC) for applications to SAW device technology. OFC is the use of orthogonal frequencies to encode a signal, which spreads the signal bandwidth in a manner similar to a fixed M-ary frequency shift signal. Also, a pseudo noise (PN) sequence can be added for additional coding. The OFC technique provides a wide bandwidth spread spectrum signal with all the inherent advantages obtained from the time-bandwidth product increase over the data bandwidth. The theory of OFC is presented and discussed; defining the fundamental equations and showing the time and frequency domain relationships. The application of OFC to SAW devices for tagging will be introduced.

I. Introduction

The use of orthogonal frequencies for a wealth of communication and signal processing applications is well documented.[1,2,3] Orthogonal frequencies are often used in an M-ary frequency shift keying (FSK) system.[4] There is a required relationship between the local, or basis set, frequencies and their bandwidths which meets the orthogonality condition. If adjacent time chips have contiguous local stepped frequencies, then a stepped chirp response is obtained.[5] This paper presents the concept of orthogonal frequency coding (OFC) for SAW communication, tag and sensor applications. OFC is a spread spectrum technique for encoding the SAW device which has the inherent advantages of processing gain and security. The technique allows both frequency and PN coding, and use of a chirp interrogation signal for increased power. This paper presents the basic theory, the OFC coding approach, a comparison to conventional PN coding, and SAW device implementation concepts.

II. Orthogonal Frequency Definitions and Review

Consider a time limited, nonzero time function defined as

$$h(t) = \sum_{n=0}^{N} a_n \cdot \phi_n(t)\ , \quad |t| \le \frac{\tau}{2}$$

$$= 0\ , \quad |t| \ge \frac{\tau}{2} \qquad (1)$$

$$\text{where} \quad \phi_n(t) = \cos\left(\frac{n \cdot \pi t}{\tau}\right)$$

The function, $\varphi_n(t)$, represents a complete orthogonal basis set with real coefficients a_n. The members of the basis set are orthogonal over the given time interval if

$$\int_{\frac{-\tau}{2}}^{\frac{\tau}{2}} \phi_n(t) \cdot \phi_m(t)\, dt = K_n\ , \quad n = m \qquad (2)$$

$$= 0\ , \quad n \ne m$$

where K_n = constant.

Given the basis set and constraints, two functional descriptions are obtained which have the forms:

$$h1(t) = \sum_{n=0}^{N} a_n \cdot \cos\left(\frac{2n \cdot \pi t}{\tau}\right) \cdot \frac{rect(t)}{\tau} \qquad (3a)$$

$$h2(t) = \sum_{m=0}^{M} b_m \cdot \cos\left[\frac{(2m+1) \cdot \pi t}{\tau}\right] \cdot \frac{rect(t)}{\tau} \qquad (3b)$$

Each cosine term in the summations in (3) represents a time gated sinusoid whose local center frequencies are given by

$$f_n = \frac{n}{\tau} \quad \text{and} \quad f_m = \frac{(2m+1)}{2\tau} \qquad (4)$$

In the frequency domain the basis terms are well known Sampling functions with center frequencies given in (4). From (4), $f_n \cdot \tau$ must be an integer, which requires an integer number of wavelengths at frequency f_n, and similarly there must be an integer number of half wavelengths at f_m. These are required conditions of the orthogonality of the basis functions. Given that each basis term is a Sampling function, then the null bandwidth is known to be $2 \cdot \tau^{-1}$. The overall frequency response is defined given the choice of function in (3), the basis frequencies of interest, the weight of the basis function, and either the bandwidth or the time length.

Figure 1 shows an example of the Sampling function basis frequency response terms described in time from (3) normalized to center frequency and having all weights of unity. Notice that the center frequency spacing is half the

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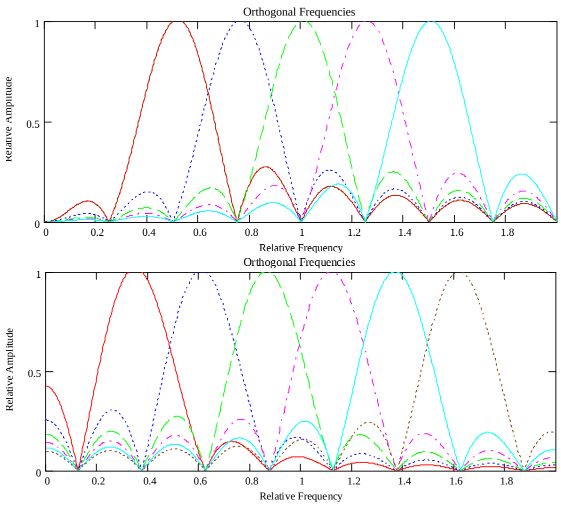

Figure 1 Example of the five and six Sampling function frequency response terms, described in time, from (3a) and 3(b), respectively, normalized to center frequency and having all weights of 1.

null bandwidth and that the center frequencies between the two plots are offset by ¼ the null bandwidth. The time descriptions in (3) yield a superposition of the selected basis functions over the fixed time interval which yields a linear group delay.

III. Orthogonal Frequency Coding Concept

A. Bit Function Description

A time function, $g_{bit}(t)$, having a time length, τ_B , is defined as the bit length where the bit will be divided into an integer number of chips such that

$\tau_B = j \cdot \tau_C$, for j=1,2...J; where J=number of chips (5)

Substituting in equations (1) - (4), $\tau_B = j \cdot \tau_C$ and $\tau = \tau_C$; all equations remain valid since $\tau = j \cdot \tau_C$ is periodic. The kernel for each chips time function is given by

$$h(t, f_{0j}) = a_j \cdot \cos(2 \cdot \pi \cdot f_{0j} \cdot t) \cdot \mathrm{rect}\left(\frac{t}{\tau_c}\right) \qquad (6)$$

The time function for each chip is

$$h_{chip}(t, f_{0j}, j) = h(t - j \cdot \tau_c, f_{0j}) \qquad (7)$$

and the complete time function for a data bit is

$$g_{bit}(t) = \sum_{j=1}^{J} h_{chip}(t, f_{0j}, j) \qquad (8)$$

where: j= 1..J is the j^{th} chip within the bit and f_{0j} is the center frequency of the j^{th} chip subject to conditions in (4). In order to build the desired time function: 1) a_j=1 for all j and 2) the bit null bandwidth is $BW_{bit} = J \cdot 2 \cdot \tau_c^{-1}$ which means that f_{01} through f_{0J} form a contiguous set, similar to Figure 1. The conditions, however, do not require that the local frequency of adjacent chips, that are contiguous in time, must be contiguous in frequency. In fact, the time function of a bit provides a level of frequency coding by allowing a shuffling of the chip frequencies in time. Figure 2 shows a 7 chip sequence for which each local frequency meets the criteria of (4), and there are an integer number of half wavelengths in each chip. The seven local chip frequencies are contiguous in frequency but are not ordered sequentially in time and the chip weights are all unity. If the local chip frequencies were ordered high to low or low to high, the time sequence would be a stepped down-chirp and up-chirp, respectively. The start of the chip carrier frequency begins at zero amplitude as seen in Figure 2; a condition of the orthogonality condition.

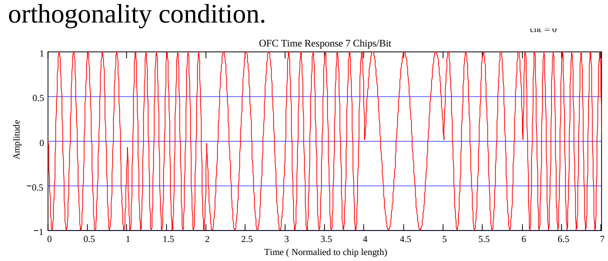

Figure 2 Example of a 7 chip time function. Time is normalized to a chip length. The lowest and highest chip frequencies have 2.5 and 9.5 cycles, respectively.

The given chip sequence represents the OFC for the bit. If there are J-chips with J different frequencies in a bit, then there are $J \cdot (J-1)$ possible permutations of the frequencies within the bit. A signal can be composed of multiple bits, with each bit having the same OFC or differing OFC. For the case of a signal, J-chips long and having a single carrier frequency, the signal is a simple gated RF burst τ_B long. The frequency responses of a 7 bit OFC and a single carrier signal are shown in Figure 3, with both time functions normalized to unity and having identical impulse response lengths. The single carrier is narrowband and has approximately 17 dB greater amplitude at center frequency, as compared to the OFC (J=7) which has a much

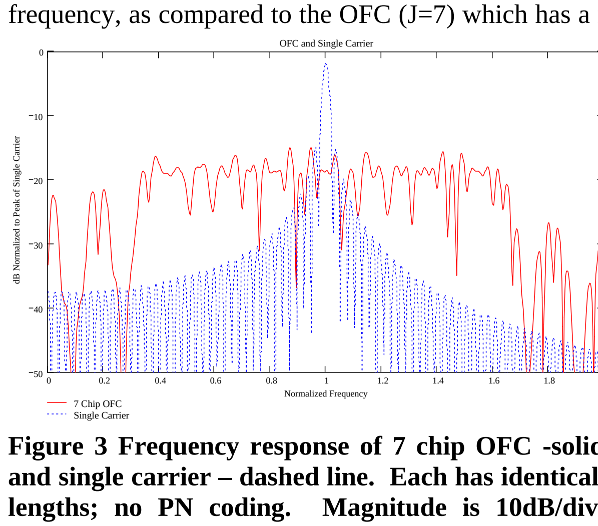

Figure 3 Frequency response of 7 chip OFC -solid line and single carrier – dashed line. Each has identical time lengths; no PN coding. Magnitude is 10dB/div and frequency is normalized to f0.

wider bandwidth. The time domain autocorrelation for the signals is shown in Figure 4. The peak autocorrelation is exactly the same, but the OFC compressed pulse width is approximately $.28 \cdot \tau_C$, as compared to the single carrier compressed pulse width of approximately a bit width, $\tau_B = 7 \cdot \tau_C$. This provides the measure of the processing gain (PG), which is the ratio of the compressed pulse width to bit length, or in this case PG= 49.

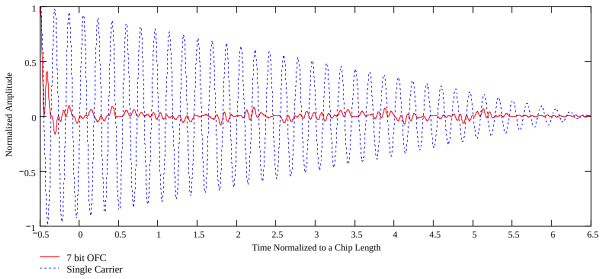

Figure 4 Time autocorrelation (1/2 length) of single carrier BPSK (-dashed line) and 7 chip OFC (-solid line) signals having identical time lengths. Amplitudes are normalized to the same value. Time is normalized to a chip length. Peak compressed pulses are identical.

B. PN Coding of the OFC Basis Function

In addition to the OFC coding, each chip can be weighted as ± 1, giving a PN code in addition to the OFC, namely PN-OFC. This does not provide any additional processing gain since there is no increase in the time bandwidth product, but does provide additional code diversity for tagging. Figure 5 shows the autocorrelation of a 7 bit Barker code applied to an OFC and a single carrier frequency. The PN code has a compressed pulse width of $2 \cdot \tau_C$, or a PG_{PN}=7 as compared $PG_{PN\text{-}OFC}$=49. The compressed pulse width of the OFC is a function of the bandwidth spread and not the PN code; yielding comparable pulse-width and sidelobes results, as seen in Figs. 4 (no-PN-code) and 5 (with-PN-code).

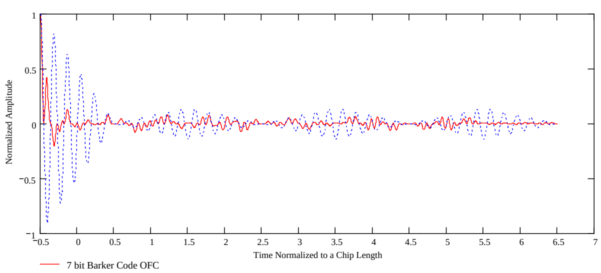

Figure 5 Time autocorrelation (1/2 impulse length) of a single carrier PN code (-dashed line) and PN-OFC (solid line) having a 7 chip Barker code modulating the chips of both signals. Time is normalized to a chip length.

The PN-OFC has an increased PG and a narrower compressed pulse peak over just the PN sequence, proportional to the bandwidth spreading of the OFC. Figure 6 compares the PN-OFC and conventional PN frequency response; the bandwidth is spread based on the OFC design.

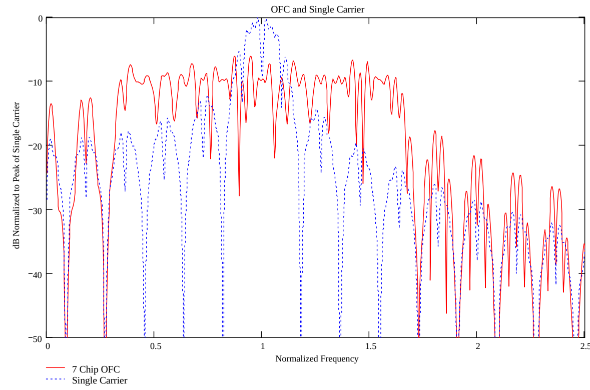

Figure 6 Frequency response of 7 chip PN-OFC (-solid line) and single carrier PN (- dashed line). Each has identical time lengths; magnitudes are normalized to the time amplitude peak of the PN response (10dB/div).

IV. OFC SAW Device Applications

The PN-OFC can be applied to SAW devices for communication, tagging and sensors. The following discussion will demonstrate the application to a SAW tag system. A proposed tag is designed having a center frequency of 235 MHz, composed of a 3-bit, 7 chip Barker code with $\tau_c = .1$usec, using 7 reflectors each having a different center frequency dependent on the electrode period. For this example, the reflectors are assumed to have equal reflectivity and have a rect time function response. A device schematic is shown in Figure 7. The input transducer is wideband and its effect is assumed negligible for this example. The OFC tag impulse response has uniform

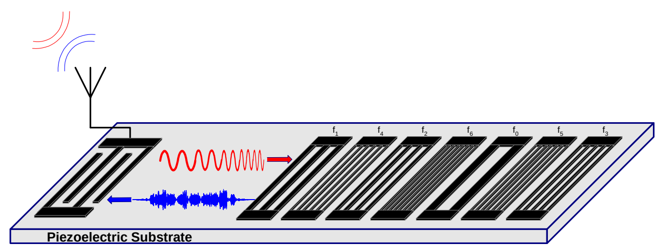

Figure 7 Schematic of 7 chip/1bit SAW OFC tag. Each reflector is a chip long and has a reflector period corresponding to the desired chip frequency.

amplitude versus time and is 21 chips long, as shown in Figure 8. The tag is interrogated with a linear stepped up-chirp having the same center frequency, time length and bandwidth as one bit. By using a chirp signal, the interrogation signal power is increased over that of a simple RF burst. The re-transmitted signal from the tag is 28 chips long due to the convolution of the interrogation chirp and tag impulse response; producing a noise like signal, as seen in Figure 8. The tag response is a spread spectrum signal which is wideband and has inherent security. Since the chips have orthogonal frequencies, there is no intersymbol interference with overlapping chips, unlike a conventional PN sequence. At the receiver the tag signal is filtered through the matched filter, a linear stepped down chirp, which unscrambles the code sequence, as seen in Figure 8, where the reconstructed signal is approximately 21 chips long, but having some amplitude modulation. The signal is

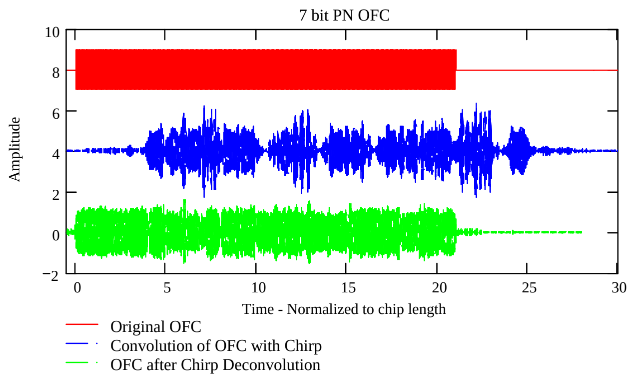

Figure 8 Top trace is 7 chip/3 bit PN-OFC signal; middle trace is the convolution of PN-OFC; lower trace is the OFC after the chirp matched filter process. Scale is relative amplitude versus time normalized to a chip length.

then match filtered with the coded PN-OFC producing the correlated compressed pulse as shown in Figure 9. The resulting compressed pulse is approximately $.28\,\tau_c$ long, yielding the processing gain of 49. Figure 9 shows the ideal convolution of the OFC signal and the system simulation.

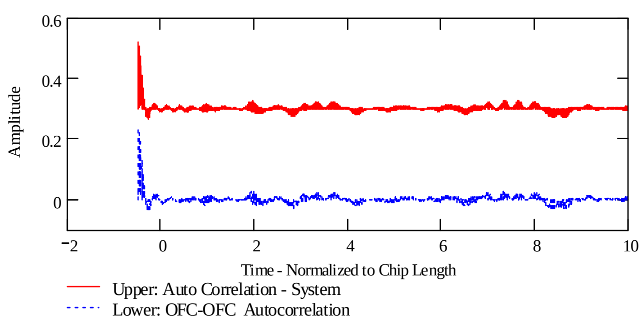

Figure 9 The SAW system simulation autocorrelation (1/2 length) of the PN-OFC (upper) and the auto correlation of the ideal PN-OFC (lower). Compressed pulse width and sidelobes are nearly identical. Plot is linear amplitude and time normalized to a chip length.

The compressed pulses are nearly identical demonstrating that the chirp interrogation signal and matched filter process accurately reconstructs the desired tag signal. Figure 10 shows the autocorrelation and cross correlation of two differing 7 chip, 3 bit PN-OFC codes. The cross correlation is comparable to the sidelobes of the autocorrelation signal, demonstrating good discrimination between codes.

V. Discussion and Conclusion

This paper has presented the concept of orthogonal frequency coding (OFC) for applications to SAW device technology. The OFC technique provides a wide bandwidth

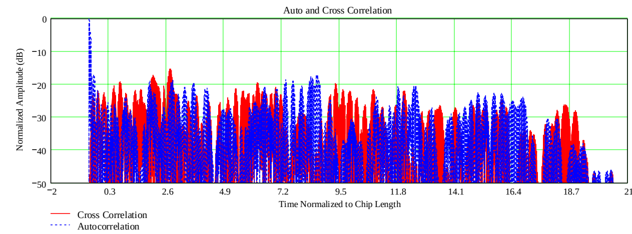

Figure 10 The normalized autocorrelation (- dashed) and cross correlation (-solid) of two differing 7 chip, 3 bit PN-OFC codes. The cross and auto correlation sidelobes are comparable. Magnitude is in dB (10 dB/div) and time normalized to a chip length; ½ IR shown.

spread spectrum signal with all the inherent advantages obtained from the time-bandwidth product increase over the data bandwidth. The theory of OFC was presented and discussed; defining the fundamental equations and showing the time and frequency domain relationships. The OFC concept allows for a wide bandwidth, chirp interrogation, frequency and binary coding per bit, a reduced compressed pulse width as compared to a PN sequence, and a secure code. This approach can be applied to ultra-wide-band applications since the fractional bandwidth can exceed 20%. The approach can be used in a multi-tag or sensor environment by using proper coding techniques. A SAW tag example demonstrated the coding approach and showed good auto and cross correlation results.

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